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PYROLYSIS

PYROLYSIS SYSTEM EVALUTION STUDY

CONTRACT No. NAS 9-14306

Final Report

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Hamilton Standard
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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

1.0 INTRODUCTION

Hamilton Standard, under Contract NAS 9-14306, has conducted an evaluation of two different pyrolysis concepts which recover energy from solid waste in order to determine the merits of each concept for integration into a Integrated Utility System (IUS). The two concepts evaluated were a Lead Bath Furnace Pyrolysis System being designed and tested by Barber Colman Co. and a Slagging Vertical Shaft, Partial Air Oxidation Pyrolysis System demonstrated by the Urban Research and Development Corporation (URDC). Both concepts will produce a fuel gas from the IUS waste and sewage sludge which can be used to offset primary fuel consumption in addition to the sanitary disposal of the waste.

The study evaluated the thermal integration of each concept as well as the economic impact on the IUS resulting from integrating each pyrolysis concept. For reference, the pyrolysis concepts were also compared to incineration which was considered the baseline IUS solid waste disposal system.

In the conduct of the study, Hamilton Standard employed the consulting services of Arthur D. Little as chemical process consultants, K. T. Lear Associates as waste management consultants, and URDC for preliminary design information concerning the URDC concept. Hamilton Standard greatly appreciates the efforts of these consultants for their assistance in assessing the available design information and in formulating Hamilton Standard's conclusions presented in this report.

1.0 (Continued)

The body of the final report presented herein summarizes the pertinent results of the study and the general logic behind these results. Detail technical and economic discussions supporting the study summary are organized by topic and are presented in the Appendices of this report. Also contained in the Appendices are the comments concerning the two pyrolysis concepts which were prepared by Arthur D. Little consultants and some supporting test information compiled by K. T. Lear Associates.

2.0 STUDY CONCLUSIONS

The major objective of Pyrolysis System Evaluation Study Program was to determine which Pyrolysis concept, URDC's or Barber Colman's was best suited for an IUS. The evaluation of the two concepts was made on indepth technical and economic considerations.

The study results which are presented in this report, clearly indicate that the URDC concept is the better Pyrolysis system for development and integration into an IUS. In addition to this conclusion, the following secondary conclusions were reached:

Pyrolysis is technically and economically superior to incineration for IUS.

Pyrolysis can reduce IUS annual primary fuel consumption by 13.7%.

Pyrolysis gas must generate electricity in order to obtain maximum benefit from the energy in the IUS refuse.

Either Pyrolysis concept needs test evaluation and data mapping to achieve commercial status.

The URDC Pyrolysis concept is appropriate for gasification of high proportions of coal mixed with the IUS refuse and for gasification of some proportion of residual oil mixed with the refuse.

2.0 (Continued)

The Barber Colman Pyrolysis concept is appropriate for gasification of up to 100% residual oil.

3.0 CONDUCT OF STUDY

The first study activity was to conduct an anaytical evaluation of the URDC system mass and energy balance and to verify the URDC and Barber Colman Pyrolysis gas compositions. These results are contained in Appendix A. From this point the IUS/ Pyrolysis integration study began.

Evaluation criteria were established with the NASA for selecting one of the two Pyrolysis concepts. These criteria are contained in Appendix I4. A baseline IUS was defined which was generally consistent with the 1000 apartment unit size of the NASA MIUS study. Ground rules for the study were established with the NASA and are contained in Appendix I3. Preliminary designs of both the URDC and Barber Colman Pyrolysis concepts were made for the 1000 apartment unit size IUS (6 tons per day solid waste plus 4 tons per day of sewage sludge).

Definitions of these preliminary designs are contained in Section 5.0 and some further details in Appendix B and C. During the preliminary design of the Pyrolysis subsystems, work was also underway on the baseline IUS. The results of this activity are contained in Section 6.0 and some further detail in Appendix D. The baseline IUS work and the Pyrolysis subsystem definitions were then integrated into complete IUS employing Pyrolysis for energy recovery from waste. The results of the integration task are contained in Section 7.0 and Appendix E.

3.0 (Continued)

After completing the above Pyrolysis subsystems and integrated IUS/Pyrolysis technical and economic activities the selection evaluation was conducted. These results are presented in Section 4.0 and with further detail in Appendix F, G and H. Information is provided on a village complex size IUS and on 250 ton per day Pyrolysis units. This information was generally scaled up from the detail 1000 apartment unit IUS work. During the entire conduct of the study, Arthur D. Little, K T Lear and URDC were used as consultants. The information concerning the Barber Colman concept was supplied by NASA and directly by Barber Colman at two different meetings at the NASA.

The final study activity was to prepare a preliminary Pyrolysis Development Program Plan and a preliminary Pyrolysis Development Program Test Plan. These plans are contained in Appendix I1 and I2 respectively.

4.0 SYSTEM SELECTION

4.1 Introduction

The selection of one of the two pyrolysis concepts for application in an IUS was based on criteria established with the NASA early in the study program. These criteria, as well as the merit weighting of each criteria, are discussed in detail in Appendix I4. These criteria are:

- Cost of each concept for an IUS
- Integration aspects of each concept in an IUS
- Development status of each concept
- Applications of each concept other than IUS

Each of these criteria is discussed in this section as they relate to the URDC and the Barber-Colman pyrolysis concepts. Each of the concepts was also assigned a point score. The point scoring is contained in Appendix I5. As reflected in the following discussion, the URDC system was selected as the better system for use with an Integrated Utility System.

4.2 Cost Comparison

In order to obtain a reasonably precise economic comparison of the two concepts, each pyrolysis subsystem was integrated into a complete IUS system. In this way, the synergistic effects on other subsystems could be taken into account. All economic analyses were calculated on a delta basis to a baseline IUS. The

4.2 (Continued)

ground rules for this approach are contained in Appendix E3. The cost of incineration, which was the IUS baseline solid waste processing system, was extracted in total from the IUS costs and used for comparison purposes with the pyrolysis concepts. The economic comparisons of the two pyrolysis concepts were made for an IUS using a diesel generator for electrical power supply and also using fuel cells for electrical power supply. Waste management subsystem duty cycles of 24 hours per day, 6 days per week and 8 hours per day, 7 days per week were used for the economic study in accordance with contractual direction.

The economic comparison of the two pyrolysis concepts with incineration as a reference is shown in Tables 1 and 2. The cost data shown in the tables are based on a mid-1974 dollar present value calculation procedure which is defined in Appendix E4. It is clear from this cost information that the URDC concept is the lowest cost approach. In the case of eight-hour a day operation, the URDC pyrolysis concept is profitable which is indicated by the negative number on the twenty year total cost line. This profit picture results from the significant reduction in labor which is possible when three shift operation is not required even considering that the capital cost is higher due to the larger equipment necessary to process a day's waste in eight hours. An energy value of $1.75 per million Btu's (HHV) was

Table 1

ECONOMIC COMPARISON - BASELINE IUS

(DIESEL POWER, 24 HOUR/DAY, 6 DAY/WEEK)

	INCINERATION	URDC	BARBER-COLMAN
CAPITAL OUTLAY	$ 63,500	$150,900	$239,800
OPERATION AND MAINTENANCE	$383,000	$305,800	$322,200
ENERGY COST AVOIDANCE	$ 38,900	-$350,700	-$135,300
TWENTY YEAR TOTAL COST	$485,400	$106,000	$426,700

(DIESEL POWER, 8 HOUR/DAY, 7 DAY/WEEK)

	INCINERATION	URDC	BARBER-COLMAN
CAPITAL OUTLAY	$149,200	$231,500	$347,000
OPERATION AND MAINTENANCE	$138,000	$ 61,300	$ 88,000
ENERGY COST AVOIDANCE	$ 51,300	-$345,300	-$133,900
TWENTY YEAR TOTAL COST	$338,500	-$ 52,500	$301,100

TABLE 2

ECONOMIC COMPARISON - BASELINE IUS

(FUEL CELL POWER, 24 HOUR/DAY, 6 DAY/WEEK)

	INCINERATION	URDC	BARBER-COLMAN
CAPITAL OUTLAY	$ 64,000	$133,600	$209,000
OPERATION AND MAINTENANCE	$356,500	$290,500	$306,900
ENERGY COST AVOIDANCE	-$ 87,600	-$354,000	-$217,100
TWENTY YEAR TOTAL COST	$332,900	$ 70,000	$298,800

(FUEL CELL POWER, 8 HOUR/DAY, 7 DAY/WEEK)

	INCINERATION	URDC	BARBER-COLMAN
CAPITAL OUTLAY	$149,700	$201,400	$316,200
OPERATION AND MAINTENANCE	$138,000	$ 46,000	$ 72,900
ENERGY COST AVOIDANCE	-$ 75,200	-$348,600	-$215,700
TWENTY YEAR TOTAL COST	$212,500	-$101,200	$173,400

4.2 (Continued)

used for energy cost avoidance. The reason for the higher cost of operation and maintenance for incineration is that a penalty was applied for ash disposal. The frit from the URDC concept and the residue from the Barber-Colman concept were considered neither a credit or a debit since it was assumed that either would be hauled away free for its economic value. It is of interest to note that incineration in a diesel powered IUS does not give a profit in energy cost avoidance. The reason is that the heat recovered from the incineration process can only be used during the winter for heating and the summer for absorption cooling, however, fuel oil must be used year round for refuse incineration. Some energy cost avoidance is realized by the incinerator in the fuel cell powered IUS since there is less waste heat generated by the fuel cells due to their higher efficiency power generation, and as a result, more of the heat recovered from incineration can be utilized. The reason for the larger energy cost avoidance for URDC is due to the higher energy recovery efficiency from the refuse by the URDC concept. This point is discussed under integration aspects below. More detail on the comparative costs of the two pyrolysis concepts is given in Appendix E5.

The above economic discussion was based on a 1000 unit IUS. Figure 1 shows the capital cost of the Barber-Colman and URDC concepts up to a 250 ton per day of municiple refuse capacity.

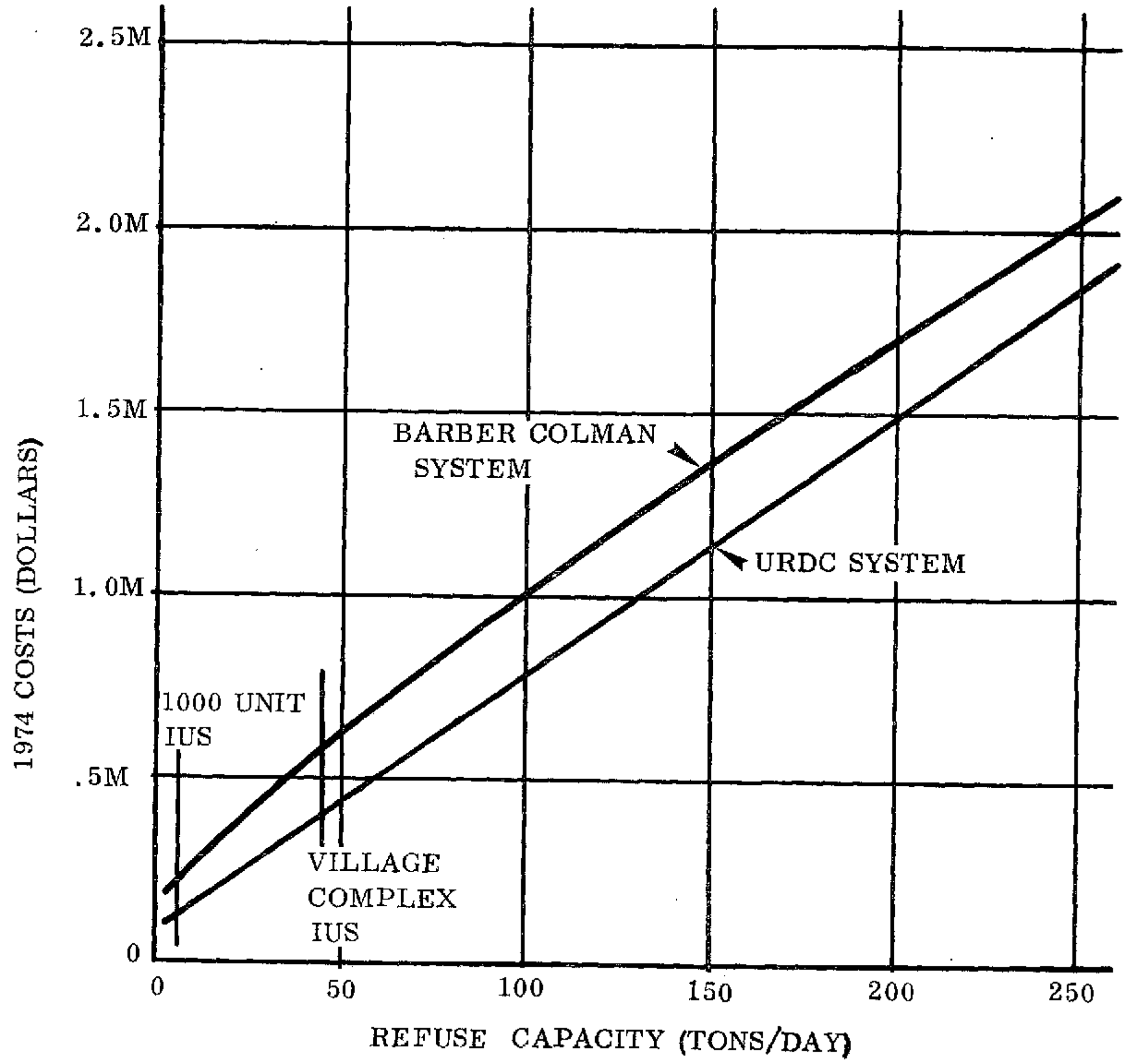
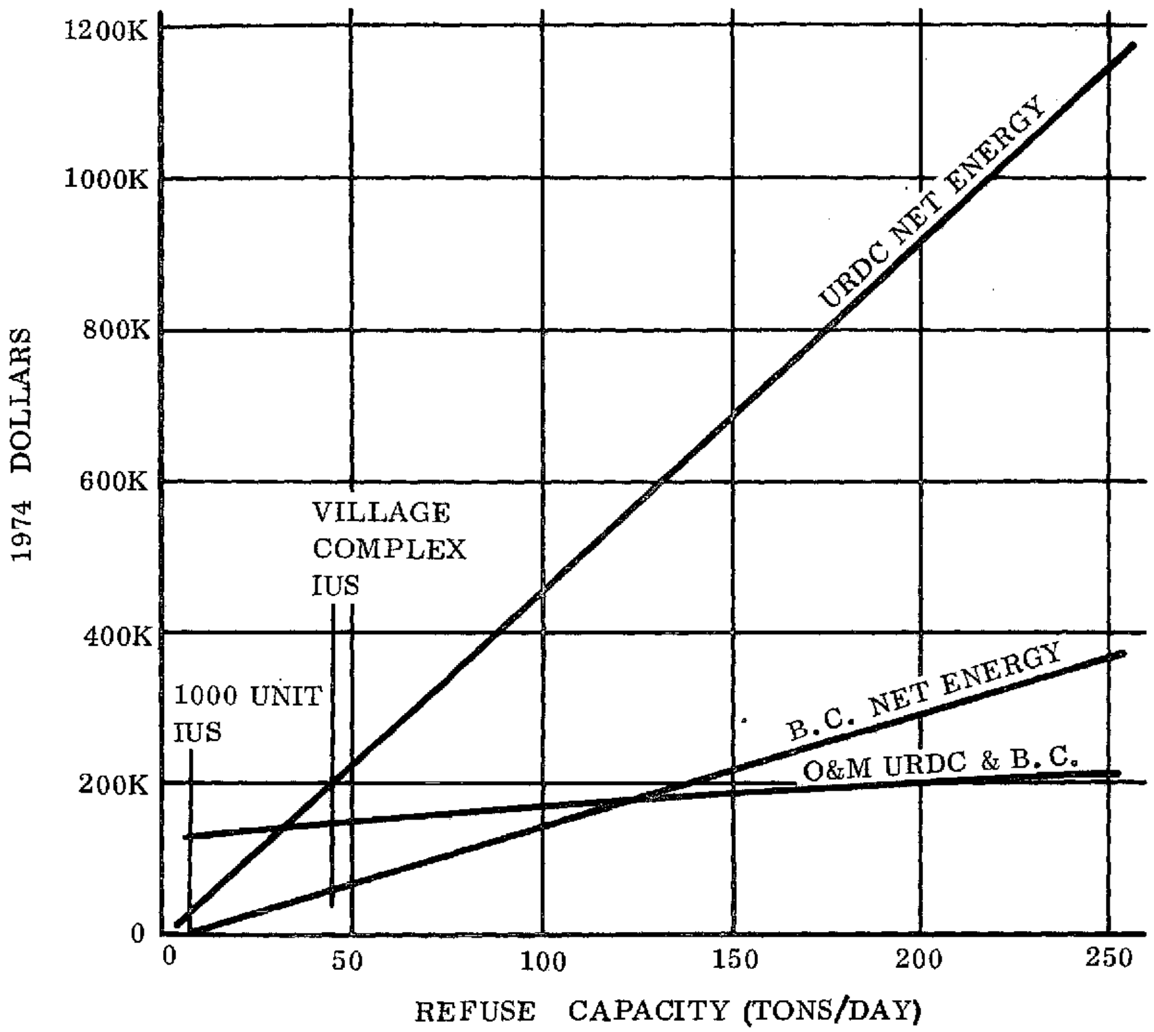


FIGURE 1
PYROLYSIS UTILITY SYSTEMS
CAPITAL COSTS

4.2 (Continued)

The 250 tons per day capacity is considered an upper size limit for both concepts. The capital costs indicated by the curves are for just the pyrolysis system hardware necessary to provide a cold clean fuel gas. The Barber-Colman system capital does not include any metal and glass separating equipment. The main reason for the Barber-Colman higher capital cost is that refuse preparation by shredding is necessary. The URDC concept will accept waste as it comes off of the packer truck. Neither concept's capital costs include refuse storage facilities, buildings or land costs. The 45 ton per day point is considered the largest probable IUS size which would be adequate for a village complex as defined in the NASA MIUS study.

The recovered energy value and the operating and maintenance cost versus system size are shown on Figure 2. The Barber-Colman system does have a slightly higher maintenance cost due to its higher capital cost and the need for shredder maintenance; however, the cost of operating labor (based on 24 hours a day operation) for both concepts overshadows the maintenance cost, and for practical purposes, the operation and maintenance is the same cost for both concepts and is shown as one line on the Figure. The value of energy recovery is significantly greater for the URDC concept. The URDC concept's value from energy recovery exceeds the operation and maintenance cost at about the



NOTE: NET ENERGY CURVES ARE BASED ON INDICATED REFUSE CAPACITY PLUS SLUDGE CAPACITY. (SLUDGE CAPACITY = .67 X REFUSE)

FIGURE 2
PYROLYSIS UTILITY SYSTEMS
ANNUAL O&M COSTS AND NET ENERGY VALUE
V.S.
REFUSE HANDLING CAPACITY

4.2 (Continued)

30 ton per day capacity. The Barber-Colman concepts value from energy recovery does not exceed the operation and maintenance cost until about 110 tons per day capacity.

4.3 Integration Aspects

The integrational aspects considered important in selecting a pyrolysis concept for an IUS are:

- Pyrolysis Gas Utilization
- Efficiency
- Flexibility
- Fire, Safety and Pollution

Each of these topics is discussed below.

4.3.1 Pyrolysis Gas Utilization

The fuel gas from both pyrolysis concepts is usable in an IUS. More importantly, the fuel gas from both concepts can be used in the electrical generation prime mover to offset primary fuel costs. This aspect is very important as can be seen from the incineration flow charts in Appendix E2 which indicate that high grade steam heat can only be used effectively during the summer and winter. Neither pyrolysis gas product can be considered an ideal fuel, since neither can be mixed directly with the primary IUS fuel. A detailed discussion on pyrolysis gas utilization which covers spark ignited engines, compression ignited

4.3.1 (Continued)

engines, fuel cells, gas turbines, boilers and burners is contained in Appendix F1. As indicated above, the pyrolysis gas must be used to generate electricity, and for IUS this is done with either diesel generators or fuel cells. These two uses are discussed below.

For the diesel case, the efficiency penalty associated with use of either pyrolysis gas is probably negligible if a spark ignited or a dual fuel compression ignition engine is used. If the gases are fumigated into the air intake of a straight oil fired diesel engine, there may be some penalty. However, the efficiency of gas utilization would be the same for both pyrolysis gases. The lower density URDC product gas used in a dual fuel engine will require a higher supply pressure to the engine to get the required energy into the engine through the gas valves. If the natural gas supply pressure were 2 psi, the corresponding pressure for URDC and Barber-Colman product gases would be 7.5 psi and 0.8 psi respectively which are relatively insignificant differences in terms of pumping. This situation would only result if 95% of the energy input to the engine were gaseous as is the typical case for dual fuel engines; however, the IUS pyrolysis gas energy input would only be about 5% to 20%. Once through the gas intake valves, both gases when mixed with the intake air will give the same energy release in the cylinder without displacing the air needed for the fuel oil combustion. This can be

4.3.1 (Continued)

seen from the fuel gas rating parameters in Table 1 of Appendix F1 which shows the fuel air mixture energy of the URDC gas, the Barber-Colman gas and natural gas to be 70, 86 and 87 Btu's per ft^3 respectively. The difference between these numbers only becomes significant at overload conditions on the engine using near 100% gaseous energy. At this point, the amount of Barber-Colman gas which could be taken into the engine would be about 5% greater.

For the fuel cell application, it can be shown that both fuels are somewhat better than the IUS primary fuel. The fuel cell is a hydrogen consumer, and the primary fuel must be reformed before it can be used by the fuel cell. The URDC product gas requires no reforming, and the Barber-Colman product gas requires less reforming than the IUS primary fuel. Introducing pyrolysis gases will introduce hardware complexities into the fuel cell system which may offset the slight efficiency advantage (URDC and Barber-Colman product gases give total fuel cell efficiency increases of 1.4% and 0.2% respectively).

The most significant comparison of the two pyrolysis gases is the heat rate required to generate a KWH of electricity. Table 3 shows this comparison. From the above discussion, it was assumed that a Btu of oil is equivalent to a Btu of pyrolysis fuel gas in the prime mover, however, when related to the refuse energy input

TABLE 3

RELATIVE HEAT RATES

FUEL	HEAT RATE (LHV)
OIL	9,720 BTU/KWH
PYROLYSIS GAS	
(URDC OR BARBER-COLMAN)	9,720 BTU/KWH
REFUSE	
URDC SYSTEM & GENERATOR	12,400 BTU/KWH
BARBER-COLMAN & GENERATOR	30,300 BTU/KWH

4.3.1 (Continued)

there is a significant difference between the concepts. This difference is due to the efficiency of energy recovery from the waste which is discussed under efficiency below.

4.3.2 Efficiency

The basis of comparison considered most meaningful for efficiency of the two Pyrolysis concepts is the savings in IUS primary fuel divided by the energy equivalent of the refuse supplied to the Pyrolysis unit. Complete baseline IUS thermodynamic flow charts are contained in Appendix D3 and integrated Pyrolysis/IUS thermodynamic flow charts are contained in Appendix E2.

A summary of results from these flow charts is shown in Table 4. The URDC concept is over 2.5 times as efficient as the Barber Colman concept for a diesel powered IUS. The baseline incinerator has an overall negative efficiency since the waste heat can only be used in the summer and winter, however, primary fuel must be used all year round for waste disposal. The Barber Colman efficiency increases somewhat for the fuel cell powered IUS since the IUS can use some of the high grade waste heat generated by the Pyrolysis unit. Less waste heat is generated by the fuel cell electrical prime mover than by a diesel electrical prime mover due to the higher electrical conversion efficiency of the fuel cell system. For these reasons the incinerator also shows a higher efficiency in the fuel cell prime mover IUS.

TABLE 4

EFFICIENCY OF PYROLYSIS IN AN IUS

FUEL CONSUMPTION WITH:	DIESEL 24 HOUR	DIESEL 8 HOUR	FUEL CELL 24 HOUR	FUEL CELL 8 HOUR
NO WASTE	107,076*	107,076	95,374	95,374
INCINERATION	108,701	109,219	91,797	92,315
SAVINGS	-1,625	-2,143	3,577	3,059
EFFICIENCY**	-8.3%	-11.0	18.3	15.6
URDC	92,437	92,663	80,596	80,822
SAVINGS	14,639	14,413	14,778	14,552
EFFICIENCY	74.8	73.7	75.5	74.4
BARBER-COLMAN	101,429	101,488	86,313	86,372
SAVINGS	5,647	5,588	9,061	9,002
EFFICIENCY	28.9	28.6	46.3	46.0

*10^6 BTU (ANNUAL)

$$** \text{ EFFICIENCY} = \frac{\text{SAVINGS}}{\text{LHV ANNUAL WASTE}} = \frac{\text{SAVINGS}}{19{,}564 \times 10^6 \text{ BTU}}$$

4.3.2 (Continued)

Subsystem efficiencies were calculated for both the URDC and the Barber Colman concepts and are discussed in detail in Appendix B3 and C3 respectively. Each concept generates a cold clean fuel gas at efficiencies of 78.4% for the URDC concept and 32.1% for the Barber Colman concept. In calculating these efficiencies no consideration was made of IUS integrational aspects and electrical power required by the Pyrolysis subsystem. The effect of integration aspects and subsystem electrical power can be seen by comparing these efficiencies with those in Table 4.

4.3.3 Flexibility

Flexibility considerations believed important to an IUS are listed below and discussed in Appendix F3.

IUS size variations
IUS supply fuel variations
Type of IUS energy needed
Waste type variations
Waste quantity variation
IUS load variations
24 hour versus 8 hour operation

Relative to an IUS and even for a utility application no significant differences could be found between the two pyrolysis systems from a size variation standpoint. Both concepts can be made smaller than the 1000 apartment unit IUS requirement (URDC's

4.3.3 (Continued)

concept would require some shredding of the refuse for smaller sizes) and both probably have an upper limit around 250 tons per day which is well above any IUS consideration.

Both Pyrolysis concepts have similar ability to interface with various IUS primary fuels as discussed under 4.3.1. If the IUS fuel is not gaseous, the Barber Colman system would require a separate source of fuel such as LP gas for start up or hot holding conditions since the type of burner used to fire the radiant tubes is only available for gas firing. Both Pyrolysis systems have the potential for supplementing the IUS primary fuel beyond the energy from the refuse by Pyrolyizing residual oil. The Barber Colman system could probably Pyrolyize 100% residual oil. The URDC system, however, could pyrolyize a considerable amount of coal along with the refuse whereas the Barber Colman system probably could not accept any coal supplement Pure pyrolysis such as the Barber Colman concept is unsuitable for coal due to the high level of fixed carbon and low level of volatiles.

For an IUS, the principle type of fuel which can be most efficiently used is one that can be supplied to the electrical generating prime mover. Both Pyrolysis fuels are suitable for this requirement as discussed in 4.3.1 and Appendix F1. Neither of the fuel gases are suitable for IUS apartment appliances for two reasons. The BTU per ft^3 level of both gases is far below

4.3.3 (Continued)

the orifice sizing of modern appliances designed to use natural gas or LP gas. The CO content of both gas is high and would probably be considered unsafe for distribution to the apartments.

Waste type, waste quantity and IUS load variations are all related and both Pyrolysis concepts would be better than incineration relative to changes in the parameters. The Pyrolysis gas from both systems will remain relatively constant for the waste type variations possible in an IUS. If some changes do result, they will not affect the operation of the prime mover to which the gas is being fed. Also waste quantity and IUS electrical load variations are not expected to have any significant effect since the contribution by Pyrolysis gas will normally be in the range of 5% to 25% and if unusually wide savings in load do happen a 2 or 3 day refuse storage capability is available. The URDC concept has the capability waste processing rates of about 50% to about 120% of design capacity. The Barber Colman concept has very low process rate capability; however, increases beyond design point present a problem since refuse may pass through the reactor without being pyrolyized.

A 24 hour a day operation is desirable for both Pyrolysis concepts due to the fire brick construction and due to the energy required to heat up the units. However, it is feasible to run both concepts for 8 hours a day and possibly more economically due to the lower labor requirement as indicated in 4.2.

4.3.4 Fire Safety and Pollution

The problems associated with meeting fire safety and pollution codes are discussed in Appendix F4 along with presenting appropriate systems engineering and design guidelines.

Both Pyrolysis concepts can meet the necessary requirements and would solve the pollution problem associated with the sanitary disposal of the IUS refuse and sewage sludge. Compared to incineration,both Pyrolysis concepts have the capability to scrub and clean a relatively small amount of fuel gas before burning rather than the need to scrub the final exhaust products of incineration. Some differences between the systems are of importance. The Barber Colman system has an added fire hazard and generates noise due to the requirement for shredding the refuse. Suitable fire suppression and muffling equipment can however, be provided to minimize these problems. The Barber Colman system may also be somewhat more hazardous around the furnace due to the high gas temperatures (800°F to 1400°F) which may ignite if exposed to air (i.e., the refuse feeds). The URDC system has low exhaust gas temperatures (200°F), however, it may be possible to get enough air into or gas out of the system to reach explosion level if proper controls are not provided.

Explosive gas sensing externally and oxygen sensing internally may be required. The residue from the Barber Colman system is expected to be acceptable for landfill, however, it will be more

4.3.4 (Continued)

polluting than the URDC frit material. The liquid effluent from both systems in an IUS configuration should not impose a significant load increase on the IUS waste water treatment subsystem. The char produced by the Barber Colman system has the potential for cleaning liquid effluents from the system to a high degree.

4.3.5 Complexity

In an IUS configuration,both Pyrolysis concepts are more complex than an incinerator of the type that would be used in an IUS range. In order to evaluate system complexity both Pyrolysis concepts can be broken down into the following elements:

Refuse handling and feeding
Thermal processing (furnace or gasifier)
Residue handling
Fuel gas processing
System control

The need for refuse shredding and associated storage bin and conveyors greatly increases the complexity of the Barber Colman system from a refuse handling and feeding standpoint. The URDC system cart dumper and feeder is based on stationary compactor technology and is about as simple as is possible to feed a closed Pyrolysis reactor.

The URDC fixed bed gasifier is about as simple mechanically as

4.3.5 (Continued)

can be imagined. The Barber Colman furnace is reasonably simple also but does have the complexity of a circulating lead bath and a mechanical device required to push residue out of the furnace.

The residue handling systems are considered approximately equal in complexity. The URDC system must deal with a molten slag while the Barber Colman system must handle a residue that doesn't flow well but doesn't freeze. The Barber Colman system requires the added step of char separation and recycle to the furnace.

Barber Colman uses a different fuel gas scrubbing train than URDC but both are similar in complexity. The fuel gas scrubbing for both concepts is less difficult than incinerator exhaust cleanup.

The control of the URDC system is simply to actuate the feed ram when the refuse is low when the system is operating at normal condition. The level sensing in the reactor requires the complexity of a ultrasonic detection device. At off design refuse feed rate conditions the airflow must be reduced or increased. The maximum feed rate is determined by particulate carry over (the gas velocity in the top of the reactor must be below about 5 ft/sec). The minimum feed rate is determined by the necessity to maintain slagging operation. The oxidation air inlet is controlled to about 1400°F for all feed rates and the

4.3.5 (Continued)

prime maximum and minimum feed rates must be determined by test but are expected to be from 50% to 120% of design feed rate. The reactor gas temperature is controlled by adding water or sludge to keep the gas temperature at about 200°F.

The Barber Colman system will probably require manual control to shield and fill the storage bin. A constant weight feed conveyor is used to feed the refuse. Insuring that the refuse is completely pyrolyized will require some control device but the technique is unknown to Hamilton Standard. Furnace temperature will require a control system. Both concepts will require controls on scrubber effluent levels. Both concepts will require similar fire safety controls.

4.4 Development Status

Neither Pyrolysis system has reached the development status of a commercially available system with guaranteed performance. The development status of the two systems is, however, significantly different. The URDC concept is related to the traditional gas producer once in common use for the production of industrial fuel gas from coal. The concept has also been demonstrated on municipal waste by URDC, Union Carbide and Torrax and as a result there is confidence that the concept can be developed to perform the intended IUS refuse and sludge disposal and fuel gas generation. The Barber Colman concept can be related somewhat to the true pyrolysis techniques explored by the Bureau of Mines, Garret and

4.4 (Continued)

Kaiser. However, the development status of the Barber Colman concept employing the circulating lead bath is unique and is only in the concept experimentation stage. There are real concerns about the workability and practical implementation of the concept.

Arthur D. Littles' comments in Appendix J1 tend to confirm these opinions on the two concepts.

The areas which will pose some development problems for the URDC concept are:

Maximize process rate and efficiency with minimum channeling and carry-over

Design of slag tap area for trouble free automatic operation

Design of hot zone wall area for minimum heat loss and maximum life.

Obtaining reliable precipitator operation and tar and oil return

All of the above development areas have been successfully demonstrated to some extent. However, they are the areas expected to be the most troublesome in reaching a commercial development status with the URDC system.

4.4 (Continued)

The Barber Colman system will have development problems in the following areas:

Completing pyrolysis with variations in refuse (examples: A 0.8" Dia. dry wood dowel at 880°F takes 19 minutes to pyrolyize: A 1.0" thick dry fir board exposed to flame takes 40 minutes to pyrolyize).

Consuming char in one recycle to extinction (Example: Steam Oxidation of char at 1700°F takes 30 minutes with a 0.5" thick bed at 2 lb/hr ft^2 loading rate).

Chemical and mechanical carry-over of lead

Removal of residue from lead

Even spreading of refuse on lead

Obtaining a reasonable hearth area (Example: Arthur D. Little in Appendix J1 calculated it would take a 212 ft^2 hearth area to process the 1000 apartment unit IUS refuse. The refuse residance time was calculated to be 1.56 hours).

Separating and returning tars and oils to reactor.

The development status of the two Pyrolysis concepts is discussed further in Appendix G.

4.5 Alternate Applications

Insofar as this study is concerned the application of pyrolysis to an IUS was the main thrust. It is, however, important in the selection and ultimate development of a pyrolysis concept to keep in mind the utility application of the concept. The alternate applications considered during the study and discussed in some detail in Appendix H were:

- Refuse Disposal
- Energy Recovery
- Resource Recovery
- Size Flexibility
- Coal Gasification

4.5.1 Refuse Disposal

The most important requirement for a refuse disposal utility is minimum-cost, environmentally-acceptable disposal. The URDC system can be considerably simplified from the IUS configuration for this application. Fuel gas scrubbing would not be required, and the raw gas would be burned in a simple conventional burner designed for raw gas. The gasification air heat would come from direct combustion of recycled raw fuel gas. There would be no liquid effluent from this configuration. The result would be an extremely simple, low cost system.

The Barber Colman system must use a clean gas for the radiant tubes. Either auxiliary fuel must be used or the fuel gas clean-up equipment would have to be retained. With these

4.5.1 (Continued)

considerations and the fact that Barber Colman's system requires shredders, the URDC system would be the more economical system for simple refuse disposal.

4.5.2 Energy Recovery

The IUS application of the two pyrolysis concepts covers to great extent the hardware and economic issues of energy recovery from waste. Only the candidate fuel uses would be broadened to include gas turbines and steam raising. The use of pyrolysis gas in these applications is discussed in Appendix F1. For the steam raising application the URDC system can be simplified as discussed in 4.5.1. The Barber Colman system probably could not be simplified but heat could be recovered from the radiant tube exhaust for steam generation, thus increasing system efficiency. From an energy recovery standpoint the Barber Colman system will suffer from the fundamental problem of low efficiency and the possibility of an economic payoff is doubtful as can be seen from the discussion in 4.2 and 4.3.2.

.5.3 Resource Recovery

The classical approach to metal, glass and fiber recovery from the refuse has been with front-end equipment prior to incineration or prior to feeding into a coal fired boiler as in the St. Louis Union Electric work. The URDC system is, within limits, compatible with front-end resource recovery. Generally the separating equipment's inefficiency allows enough combustibles,

4.5.3 (Continued)

glass and metal carry-over for proper pyrolysis system operation.

Barber Colman's system offers an approach to metal and glass recovery similar to separating metal and glass from incinerator ash. This approach has the advantage of pyrolyizing off the unwanted material from the metal and glass and making it biologically inactive. However, fiber recovery is not afforded by this approach but on the other hand a potentially usable char is available from the process.

In summary, no clear-cut selection can be made between the systems on a resource recovery basis.

4.5.4 Size Flexibility

Both Pyrolysis concepts have the same size range. On the small end, the concepts can be sized for around one ton per day. The URDC system would require refuse shredding below about five tons per day. The largest size for both concepts is probably around 250 tons per day. For larger installations, multiple units would be required and probably desirable.

4.5.5 Coal Gasification

It should be possible to gasify a high proportion of coal in combination with solid waste in the URDC fixed-bed gasifier. The relationship of the fixed-bed gasifier to the classical gas producer makes this assumption reasonable. Only test will determine the maximum quantity of coal which can be processed

4.5.5 (Continued)

with the refuse and the affect of caking vs. non-caking coals. The Barber Colman system is not suitable for coal gasification. It is worth noting that the Barber Colman system may be ideal for gasifying up to 100% residual oil. The URDC system can also gasify residual oil, however, 100% would not be feasible.

5.0 PYROLYSIS SYSTEMS DESCRIPTIONS

The salient features of the URDC and Barber Colman Pyrolysis systems are each described in the subsections which follow. Both systems are designed to process the refuse and sewage sludge generated in a typical 1000 unit apartment complex. The Pyrolysis systems operate for 24 hours per day, six days per week at an average process rate of 972 lb/hr in order to dispose of six tons per day of solid waste and four tons per day of sewage sludge generated in the apartment complex (seven days per week).

5.1 URDC Pyrolysis System

5.1.1 URDC Pyrolysis System Overview

The URDC System is a vertical shaft slagging pyrolysis process in which air is introduced to maintain partial combustion of the refuse. The heat from the combustion is used to dry the refuse and pyrolyize it. The system is illustrated schematically in Figure 3.

Additional detail is illustrated in Appendix B2. It is convenient to categorize the components as follows:

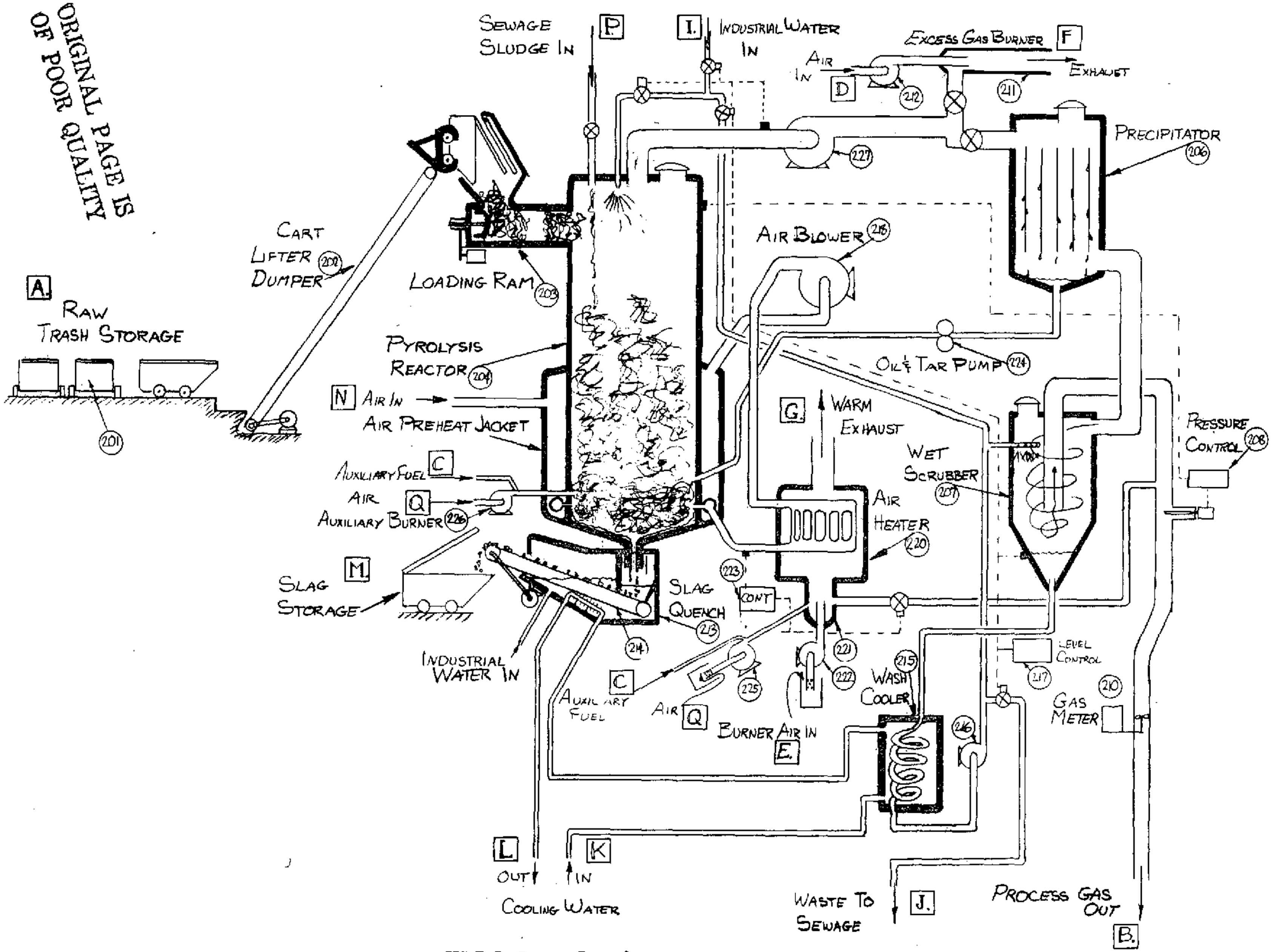
Reactor

Refuse Handling and Loading

Combustion Air Preheat

Slag Handling

Gas Cleaning



URDC Pyrolysis System Schematic

FIGURE 3

5.1.2 The Basic Pyrolysis Reaction

The URDC Pyrolysis system is built around a vertical shaft furnace reactor (or gasifier) in which refuse is fed at the top and maintained at a depth of about 3/4 of the reactor height. Heated air is introduced at the bottom to maintain a char combustion zone. The combustion zone is maintained at approximately 2400^{o}F. The combustion heat rises to drive off (pyrolyize) the product gases from the refuse above. The pyrolysis gases rise through the refuse bed drying the refuse. The gas leaves the bed nearly saturated with water vapor at 200^{o}F. From this point they are ducted away for further processing. If the refuse mixture does not have enough sewage sludge or is excessively dry, the temperature of the gases may tend to rise above the 200^{o}F range at the top of the reactor. In this case a water spray is added to provide cooling.

The refuse feed rate at the top is adjusted to maintain a relatively constant height in the reactor. As it is consumed, the refuse moves down the shaft being subjected to increasing temperatures until it reaches the char combustion zone. This heating pattern sets up identifiable zones in the column which begin with a drying zone at the top. After drying the refuse moves down through the pyrolysis zone where it is decomposed by the heat and the product gases. Some tars and oils are driven off leaving a mixture of char, metals and glass which moves into the combustion zone.

5.1.2 (Continued)

The char and the metals are oxidized in the combustion zone, and the residue is dissolved into the molten glass forming a slag. The slag is tapped from the bottom of the reactor into a water quench tank below where it is collected. The temperature of the combustion zone must be maintained above 2100°F to prevent freeze up of the slag tap hole.

The pyrolysis rate is controlled by the combustion air flow rate, and combustion zone temperature is controlled by the preheat temperature of the combustion air. As a safety feature, the reactor is maintained at a slightly positive pressure so that any leakage of gases will be out of the reactor. This prevents the possible build up of an explosive mixture within the closed system.

5.1.3 Equipment Description

The descriptions which follow are brief and discuss only the salient points of the equipment. More detailed information on each of the components is given in Appendix B1.

Reactor

The reactor is a cylindrical shaft with inside dimensions of slightly over 3 feet in diameter by 13 feet high. Refuse is introduced at the top of the reactor as is sewage sludge. The mixed waste is dried and pyrolyized as it moves down the vertical shaft. Char which reaches the combustion zone is

5.1.3 (Continued)

oxidized by the air entering the bottom. Metals are oxidized and dissolve in the inorganic oxide residue to form a single phase slag.

The reactor is divided into two sections of approximately equal length. The relatively cool upper section is an air cooled, double-walled steel structure. The lower section is lined with fine brick and insulation and is slightly larger in inside diameter than the upper section to prevent bridging of the refuse. The lower section structure is also an air cooled, double walled steel structure. The reactor concept is illustrated in Appendix B2. Some details of the air inlet, slag tap, top enclosure, air cooling, etc. are shown in that drawing.

Refuse Handling and Loading

The refuse is stored in collection carts, and is transferred to a receiving hopper at the top of the reactor by a hydraulic cart lifter/dumper. Hinged covers on the carts and one in the hopper prevent spillage during handling. A commercially available extension type compactor feeds the refuse through a duct into the reactor on signal from a ultrasonic refuse level detector in the reactor. The compacted refuse in the duct acts as a seal to prevent leakage of product gas from the reactor out through the loader. Sewage sludge is admitted directly into the reactor at the top.

5.1.3 (Continued)

Combustion Air Preheat

The combustion air supply enters the system around the reactor jacket where it gains much of the heat lost through the reactor wall. It is then heated to 1400°F in the air heater, and enters the reactor at the tuyere.

Heating of this air is accomplished by burning a fraction of the product gases with atmospheric air in the air heater. Auxiliary fuel is used only for start up.

Slag Handling

As the slag runs from the reactor, it drops into a sealed water quench tank where it hardens and fractures to a glassy frit. The frit is removed by conveyor to a storage cart. It is eventually used as construction material or it may go to land-fill without causing pollution problems or requiring cover.

Makeup water is added to the quench tank, and it is cooled to remove the slag quench heat and condense any steam which may be formed by the quenching process.

Gas Cleaning

Cleanup of the raw product gas from the reactor begins with removal of tars and oils in a precipitator. These tars and oils are pumped back to the lower section of the reactor for pyrolyizing at a higher temperature than they were originally released. The gas continues into a wet scrubber where the remaining

5.1.3 (Continued)

condensibles and the water vapor are condensed and removed. The gas is then delivered to the IUS. The scrubber water is circulated through a cooler and returned to the scrubber. Excess water is drawn from the system as the level builds up. This water may be sent to the top of the reactor if cooling is required there or it may go to waste water treatment.

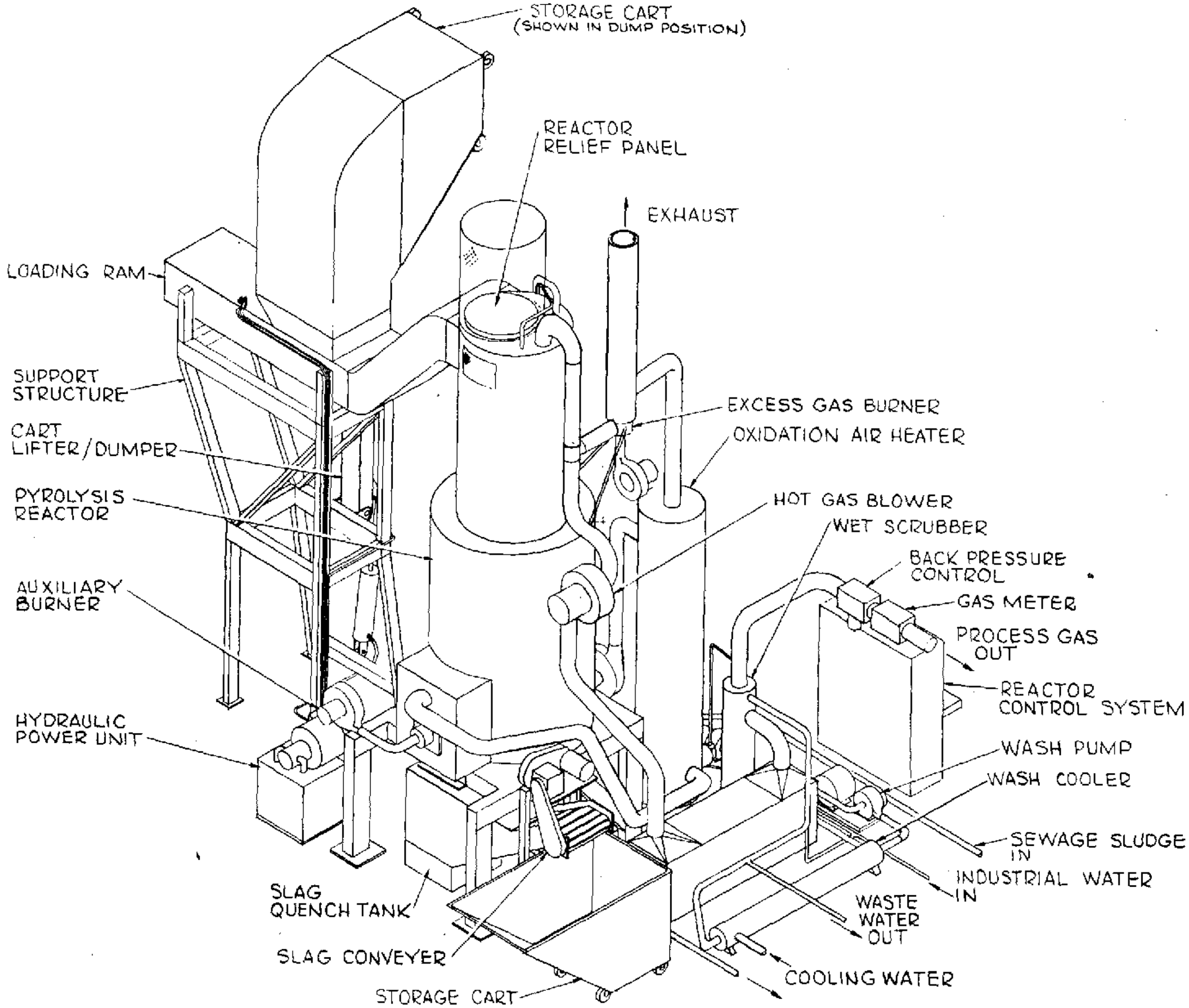
5.1.4 URDC Plant Description

The URDC Pyrolysis Plant is estimated to occupy a floor space of approximately 24 feet square, and is a maximum 24 feet high. The plant is shown pictorially in Figure 4.

The plant is arranged to minimize floor space while providing safe, convenient operation. All of the smaller equipment such as gas cleanup, the oxidation air heater, and the control panel are located in a group to one side of the reactor for visual monitoring during startup and operation. No equipment is located below the loading ram on the cart lifter dumper to preclude possible damage by falling rubbish from a storage cart with a faulty cover.

5.1.5 URDC Pyrolysis System Performance

The performance of the URDC pyrolysis system from an energy recovery standpoint is reported in detail in Appendix B3. For every pound of solid waste, processed in the system, (mixed refuse and sludge) 0.79 pounds of heated air are introduced



URDC Pyrolysis System Plant Layout

FIGURE 4

5.1.5 (Continued)

to maintain the combustion zone temperatures. The net fuel gas produced is 0.92 pounds with a lower heating value (LHV) of approximately 150 BTU/FT^3. Fuel gas properties are shown in Table 5. The energy in one pound of mixed solid waste is 2680 BTU (LHV), and the energy in the net fuel gas produced by this pound of waste is 2100 BTU (LHV). The resultant efficiency is 78.4 percent. The residue for sale or disposal is estimated to be 3 cubic feet per ton of refuse.

5.1.6 URDC Pyrolysis System Interfaces

Interface requirements for the six TPD URDC Pyrolysis System operating for 24 hours per day, six days per week are summarized in Table 6. The electrical power estimates are shwon in Appendix B5, and the details of the other interfaces may be examined in the block diagram in Appendix B2.

5.1.7 Fire Safety and Pollution

Fire safety considerations for the URDC Pyrolysis System are primarily centered around inherent problems associated with refuse handling and the manufacture of flammable gases. While experience shows that refuse handling involves fire hazards, it is manageable through proper system design providing adequate separations, detection devices, first-aid, and fire fighting equipment. The flammable gas hazards can be managed by operating the system at slightly positive pressure, monitoring performance, and providing fast acting isolation valves and vents at appropriate places in the system.

TABLE 5

URDC FUEL GAS

COMPOSITION (MOL %):

H_2	15.3%
CO	28.1%
CH_4	1.0%
C_2H_4	0.3%
C_2H_2	0.3%
CO_2	3.3%
O_2	1.4%
N_2	50.3%
	100.0%

PROPERTIES:

MOLECULAR WEIGHT:	24.5 LB/MOL
HHV:	159 BTU/FT^3 GAS
LHV:	150 BTU/FT^3 GAS
	70 BTU/FT^3 STOICH. MIX.
	78 BTU/FT^3 STOICH. COMB. PROD.
STOICHIOMETRIC VOLUME:	1.14 FT^3 AIR/FT^3 GAS
	2.14 FT^3 MIX./FT^3 GAS
	1.92 FT^3 COMB. PROD./FT^3 GAS

TABLE 6

URDC PYROLYSIS SYSTEM INTERFACES

(24 HOUR/DAY, 6 DAY/WEEK OPERATION)

INTERFACE	URDC
PRIME MOVER FUEL	894 LB/HR GAS 2,280 BTU/LB
REFUSE IN SEWAGE SLUDGE IN	583 LB/HR 389 LB/HR
AUXILIARY FUEL	191 LB/WEEK OIL
WASTE WATER TREATMENT	501 LB/HR 14.6 LB/HR CONTAM.
COOLING TOWER WATER	71,653 LB/HR 10°F DELTA T
ELECTRICAL LOAD	7.9 KW
INDUSTRIAL WATER	12 LB/HR
SOLID RESIDUE	185 LB/HR

5.1.7 (Continued)

The pyrolysis concept itself is oriented toward relieving pollution problems associated with refuse disposal. It is anticipated that the product fuel gases can be flared, if necessary, within the emissions requirements. Using the cold clean fuel gas in a prime mover will result in even cleaner emissions. The solid residue will probably be marketable as a building material, but even if it is landfilled it will be reduced in volume by a factor of about 30:1 from the raw refuse. No cover material is required.

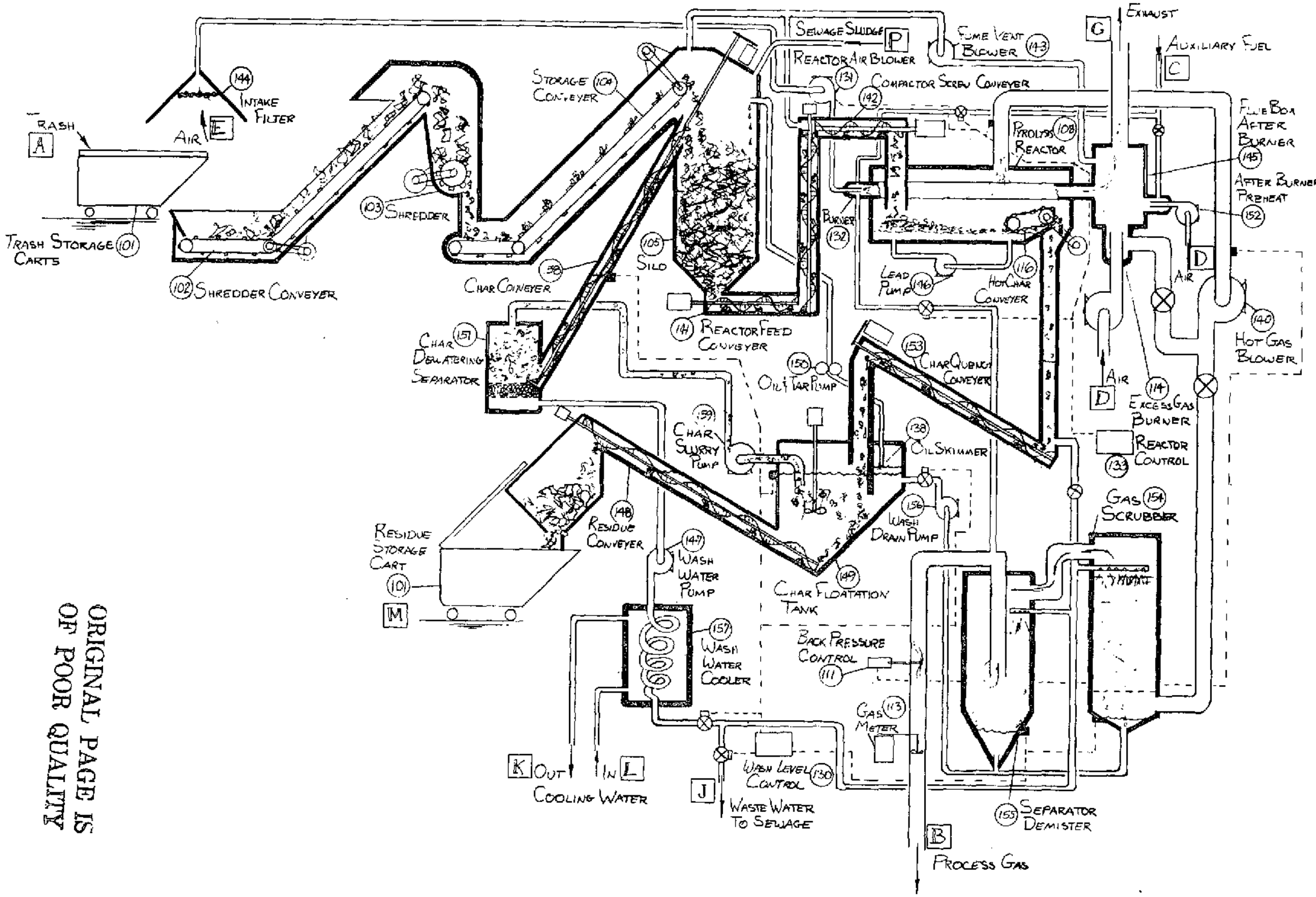
Appendix F4 provides systems engineering and design guidelines for the fire safety and pollution aspects of pyrolysis refuse disposal.

5.2 Barber Colman Pyrolysis System

5.2.1 Barber Colman Pyrolysis System Overview

The Barber Colman Pyrolysis system is designed around a radiant tube furnace reactor. Refuse is fed into the reactor at one end onto a molten lead grate. It moves through the reactor on the lead grate, as it is pyrolyized, to the opposite end where the residue is mechanically removed and the product gases are ducted away fro use of further processing.

The system is shown schematically in Figure 5. Additional detail is illustrated in Appendix C2. Essentially the same categories may be used for classifying the system components



Barber-Colman Pyrolysis System Schematic

FIGURE 5

5.2.1 (Continued)

as were used in the URDC system description:

Reactor

Refuse Handling and Loading

Heaters

Residue Handling

Gas Cleaning

5.2.2 The Basic Pyrolysis Reaction

The Barber Colman pyrolysis reactor consists of a relatively thin (1 inch) horizontal layer of shredded waste floated on a molten lead grate. The molten lead is circulated longitudually through the furnace transporting the refuse. Heat is provided from radiant tubes running parallel to the refuse bed. Exposure of the refuse to the heat drives off the product gases. A small amount of air is introduced with the refuse, but in general the reaction is isolated from the ambient by sealed enclosures.

Shredded refuse is fed from a storage silo into the reactor through a series of screw augers. The residue consisting of char, glass and metals, is mechanically skimmed or dragged off the molten lead by a chain link conveyor at the end of the lead trough. The residue is removed from the reactor for further processing. The lead is circulated back to the inlet end of the trough.

5.2.3 Equipment Descriptions

The salient features of the Barber Colman pyrolysis equipment given in the following sections. More detailed information is provided in Appendix C1.

Reactor

The Barber Colman reactor is a refractory lined steel shell with inside dimension of approximately 5 feet x 1 foot x 10 feet long. A central trough contains molten lead approximately 2 inches deep, and the residue removal mechanism is contained within the reactor. Radiant tubes pass longitudinally through the reactor. The pyrolysis gases forming the atmosphere within the reactor vary from 1400°F to 800°F of the reactor exit. Sewage sludge and refuse are received at one end and the residue and gases are removed at the opposite end.

Refuse Handling and Loading

Refuse handling up to the air lock feeder is relatively conventional. Refuse is collected and stored in carts which are dumped onto a conveyor which feeds a shredder. The shredder is followed by an intermediate storage silo which allows independent feed rates for the shredder and furnace operations. A full live bottom storage silo with demonstrated capability for removal of shredded refuse, such as the Atlas, is recommended. Sludge from waste water treatment is introduced directly into the storage silo.

5.2.3 (Continued)

Waste is removed from the silo and fed into the furnace by a series of conveyors and augers. During this feeding process refuse is compressed to a relatively high density to minimize leakage of gas out of the furnace. The feeder distributes the mixed refuse and sludge in a thin, even layer across the lead trough.

Heaters

The furnace is heated by conventional radiant tubes firing recycled, scrubbed pyrolysis gas. The gas flow within the tubes is in the same direction as the refuse travel. The air intake for the burners is taken from the refuse handling area to minimize any disagreeable effluvia originating there.

The radiant tubes exhaust in a refractory lined flue box which assure complete combustion of the heater gas. The flue box serves as a product gas flare when needed. The flue box exhausts through a stack.

Residue Processing

After removal from the reactor, the residue is quenched and washed through a screw type auger conveyor to a char flotation tank. Here the char is allowed to float thus separating from the metals and glass which settle to the bottom of the tank. The char is collected as a slurry, and pumped to a dewatering tank. From there it is augered back to the silo to be mixed with refuse and sludge and recycled through the furnace.

5.2.3 (Continued)

The char in the dewatering tank acts as a filter for the transport water which is also used for gas scrubbing. The metals, glass and inerts are augered from the char separation tank to a cart or other suitable container for disposal.

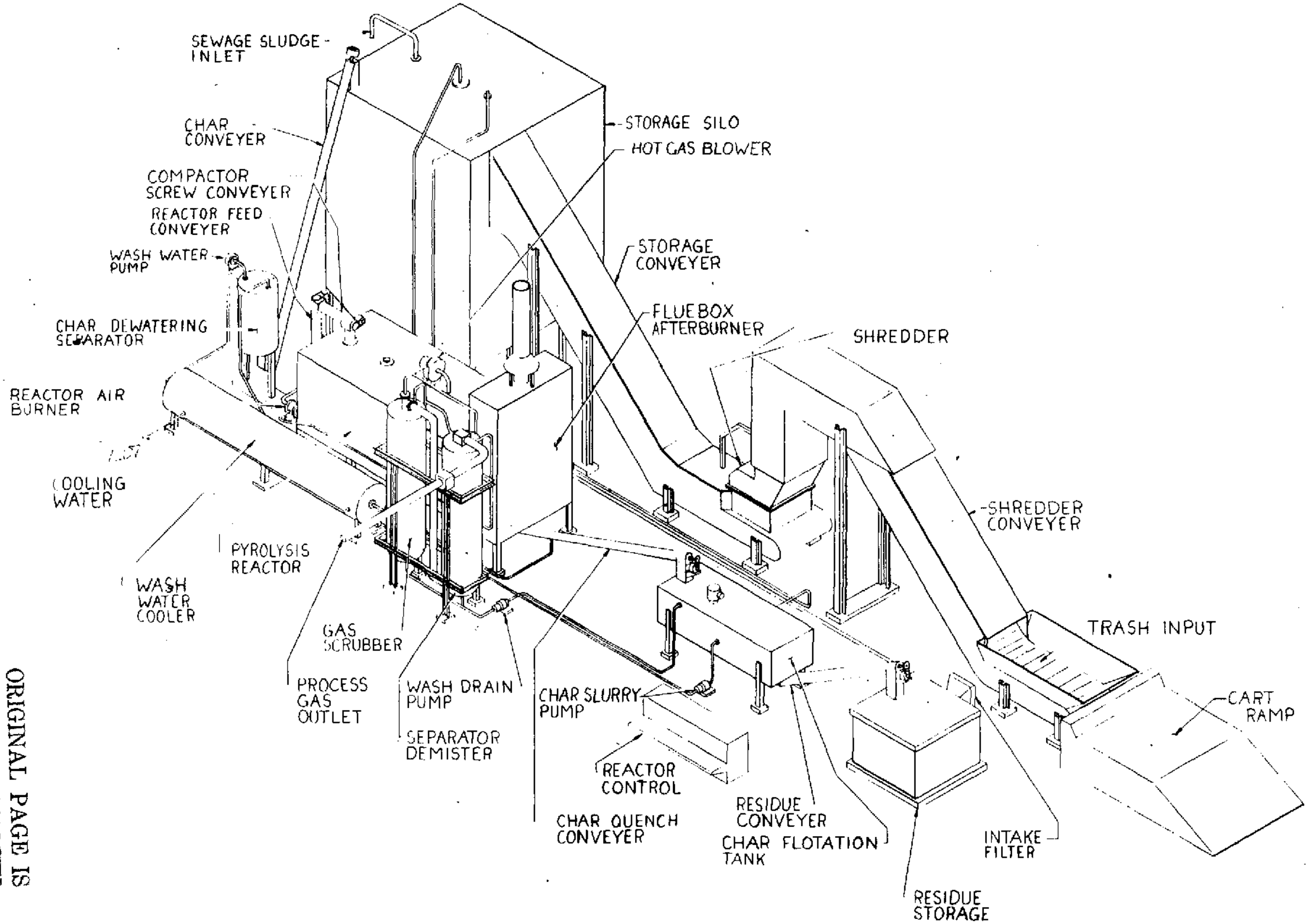
Gas Cleaning

The pyrolysis gas goes to a series of wet scrubbers which serve to quench the gas and clean it of particulates, chloride, sulfides, ammonia, and condensed tars and oils. Some of the cold clean gas is recirculated to the furnace radiant tube burners, and the rest is available for the IUS. If there is no need for gas, or if there is a malfunction in the gas clean-up train, the gas can be flared in the furnace heater flue box. The effluent from the scrubber goes to the char floatation tank and then with the char to the char dewatering separator. This serves to contact the char and waste water in order to remove the bulk of the tars and oils. The tars and oils are then recycled with the char back to the furnace rather than going with the waste water.

5.2.4 Barber Colman Plant Description

A pictorial sketch of the Barber Colman plant layout is shown in Figure 6. It occupies a floor space 65 ft. x 25 ft. and is a maximum of 18 ft. high.

The plant is arranged primarily to facilitate materials flow



Barber-Colman Pyrolysis System Plant Layout

FIGURE 6

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5.2.4 (Continued)

with the trash entrance and residue exit at the same end of the plant. Components are located to minimize floor space with all of the gas cleanup equipment located to one side of the reactor adjacent to the control panel. Most phases of plant operation are visible from the control panel area to facilitate system startup and operation.

5.2.5 <u>Barber Colman Pyrolysis System Performance</u>

Three different performance cases were calculated for the Barber Colman pyrolysis system and are presented in detail in Appendix C3. These calculations were based on varying assumptions of air or steam oxidation of the char. Since Barber Colman's intent is to operate the reactor without air, the most optimistic performance based on steam oxidation of the char has been adopted for use throughout the study. This is represented by case 3 in the Appendix C3, and the results are summarized here.

For every pound of solid waste (mixed refuse and sludge) processed through the system, a net of 0.092 pounds of fuel gas is produced with a lower heating value (LHV) of approximately 450 BTU/FT^3. Properties of the gas are shown in Table 7. The energy in one pound of mixed solid waste is estimated at 2680 BTU (LHV) and the energy in the net fuel gas produced (0.092 lb) by the pound of refuse is 860 BTU (LHV). The resultant efficiency is 32.1 percent.

TABLE 7

BARBER COLMAN FUEL GAS

(CASE 3, STEAM OXIDATION)

COMPOSITION (MOL %):

H_2	35.9%
CO	19.2%
CH_4	16.3%
C_2H_6	1.3%
C_2H_4	5.9%
C_3H_8	1.3%
CO_2	20.1%
	100.0%

PROPERTIES:

MOLECULAR WEIGHT:	20.1 LB/MOL
HHV:	494 BTU/FT^3 GAS
LHV:	449 BTU/FT^3 GAS
	86 BTU/FT^3 STOIC. MIX.
	90 BTU/FT^3 STOIC. COMB. PROD.
STOICHIOMETRIC VOLUME:	4.23 FT^3 AIR/FT^3 GAS
	5.23 FT^3 MIX./FT^3 GAS
	4.97 FT^3 COMB. PROD./FT^3 GAS

5.2.6 Barber Colman Pyrolysis System Interfaces

Interface requirements for the six TPD Barber Colman Pyrolysis System operating for 24 hours per day, six days per week are summarized in Table 8. The electrical power estimates are shown in Appendix C5, and the details of the other interfaces may be examined in the block diagram in Appendix C2.

5.2.7 Fire Safety and Pollution

Fire safety considerations for the Barber Colman Pyrolysis system are primarily centered around inherent problems associated with refuse handling, shredding, silo storage of shredded refuse and the manufacture of flammable gases. While experience shows that refuse handling involves fire hazards especially with shredders, it is manageable through proper system design providing adequate separations, detection devices and first-aid fire fighting equipment. The flammable gas hazards can be managed by operating the system at slightly positive pressure, monitoring performance, and providing fast acting isolation valves and vents at appropriate places in the system.

The pyrolysis concept itself should provide an order of magnitude improvement in relieving pollution problems associated with refuse disposal. It is anticipated that the product fuel gases can be flared, if necessary, within the emissions requirements. The solid residue will probably be marketable as a building material, but even if it is landfilled it will be reduced in volume by a factor of about 15:1 from the raw

TABLE 8

BARBER COLMAN PYROLYSIS SYSTEM INTERFACES

(24 HOUR/DAY, 6 DAY/WEEK OPERATION)

INTERFACE	
PRIME MOVER FUEL	89 LB/HR GAS 9,350 BTU/LB
PRIME MOVER RECUPERATOR	4,608 LB/HR 1,500°F
REFUSE IN SEWAGE SLUDGE IN	583 LB/HR 389 LB/HR
AUXILIARY FUEL	88 LB/WEEK PROPANE
WASTE WATER TREATMENT	431 LB/HR 3.9 LB/HR CONTAM.
COOLING TOWER WATER	90,417 LB/HR 10°F DELTA T
ELECTRICAL LOAD	27.2 KW
SOLID RESIDUE	185 LB/HR

5.2.7 (Continued)

refuse. No cover material should be required.

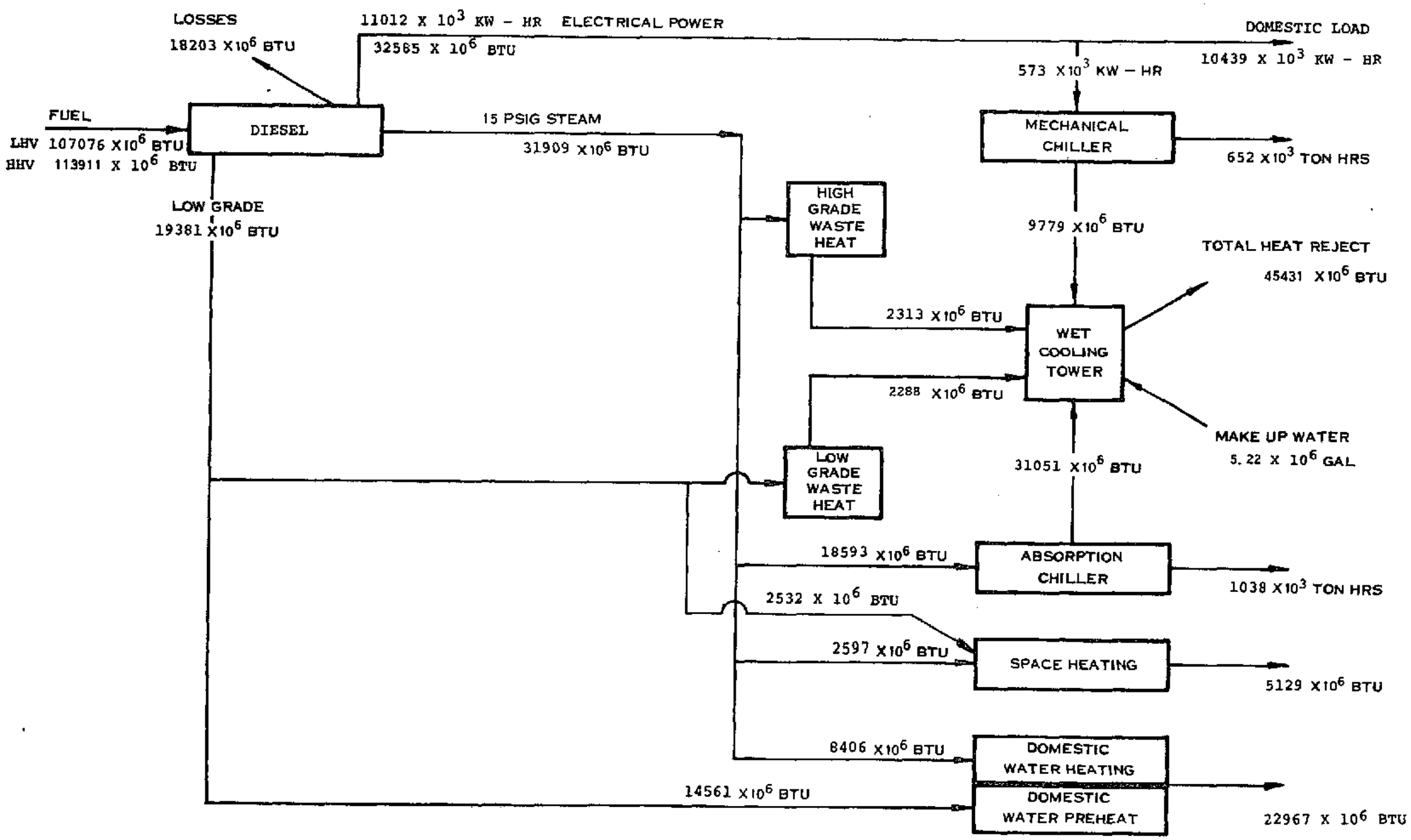
Appendix F4 discusses the fire safety and pollution aspects of pyrolysis refuse disposal. Systems engineering and design guidelines are outlined there for managing these problems.

BASELINE IUS

One of the primary objectives of the Pyrolysis System Evaluation Study was to determine the impact of integrating the two pyrolysis solid waste subsystems into an IUS. The baseline IUS used for this investigation was for a 1000 Unit Apartment Complex in Washington, D.C. with incineration as the method of solid waste and sewage sludge disposal. The IUS definition taken from the MIUS Design Study Report with some simplifying assumptions to facilitate uniformity in the pyrolysis integration investigation. Appendix D2 describes the mathematical models used for analysis of the IUS. In general these were based on the study groundrules established early in the program and shown in Appendix I3.

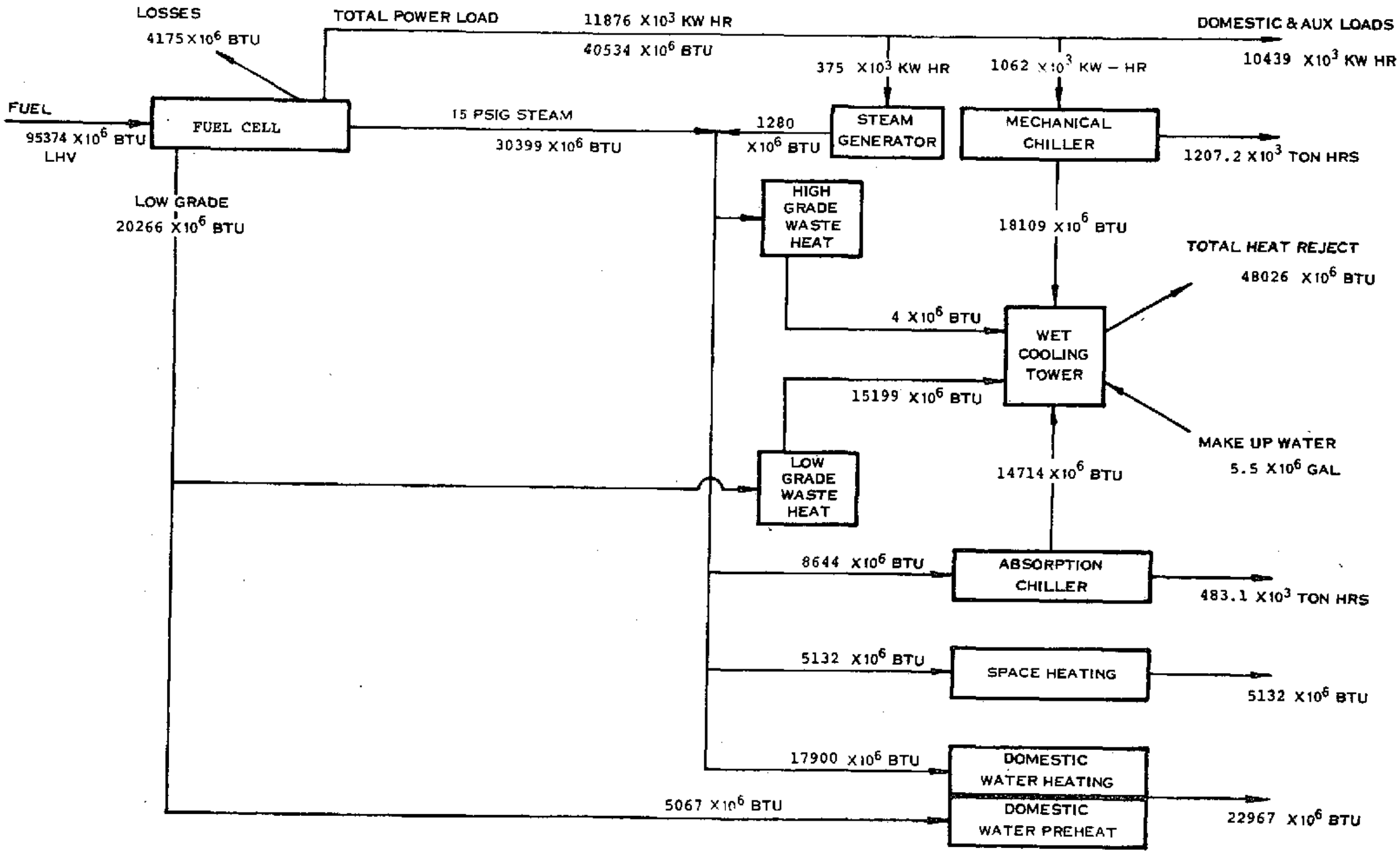
Figures 7 and 8 show the annual summation of energy flow in the IUS with no provisions for waste disposal except for collection within the apartment complex. Fuel cell and diesel electrical subsystems are both shown. Figures 9 and 10 show comparable annual summations for an IUS with an incineration subsystem for solid waste and sewage sludge disposal. The incineration subsystem includes high-grade heat recovery which is primarily used for absorption cooling in the summer. Seasonal energy charts are shown in Appendix D3 for the IUS with incineration and without solid waste disposal.

Since the primary purpose of an IUS is the conservation of energy, it is of interest to compare the annual fuel consumption



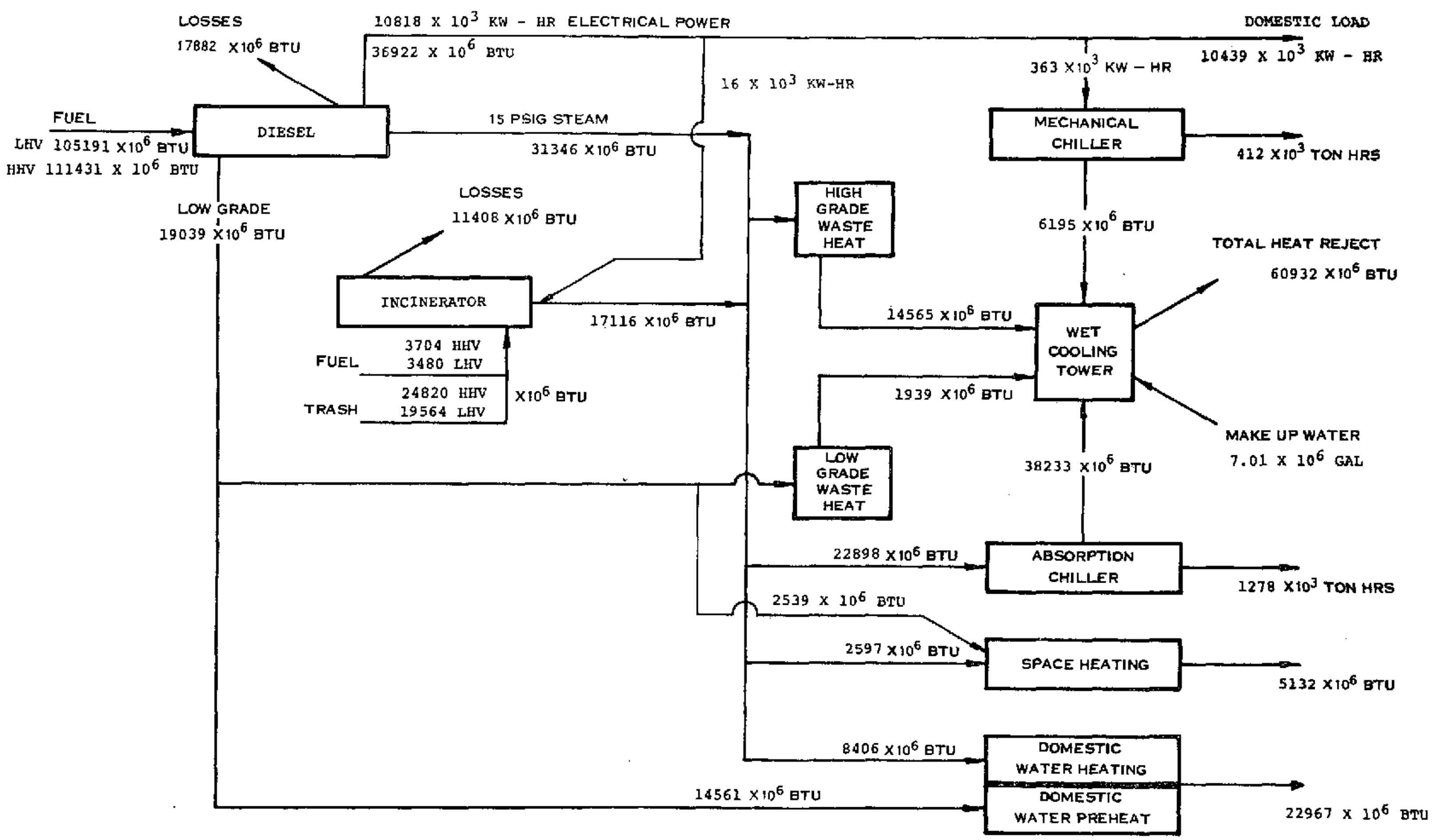
IUS - DIESEL - ANNUAL
NO WASTE DISPOSAL

FIGURE 7



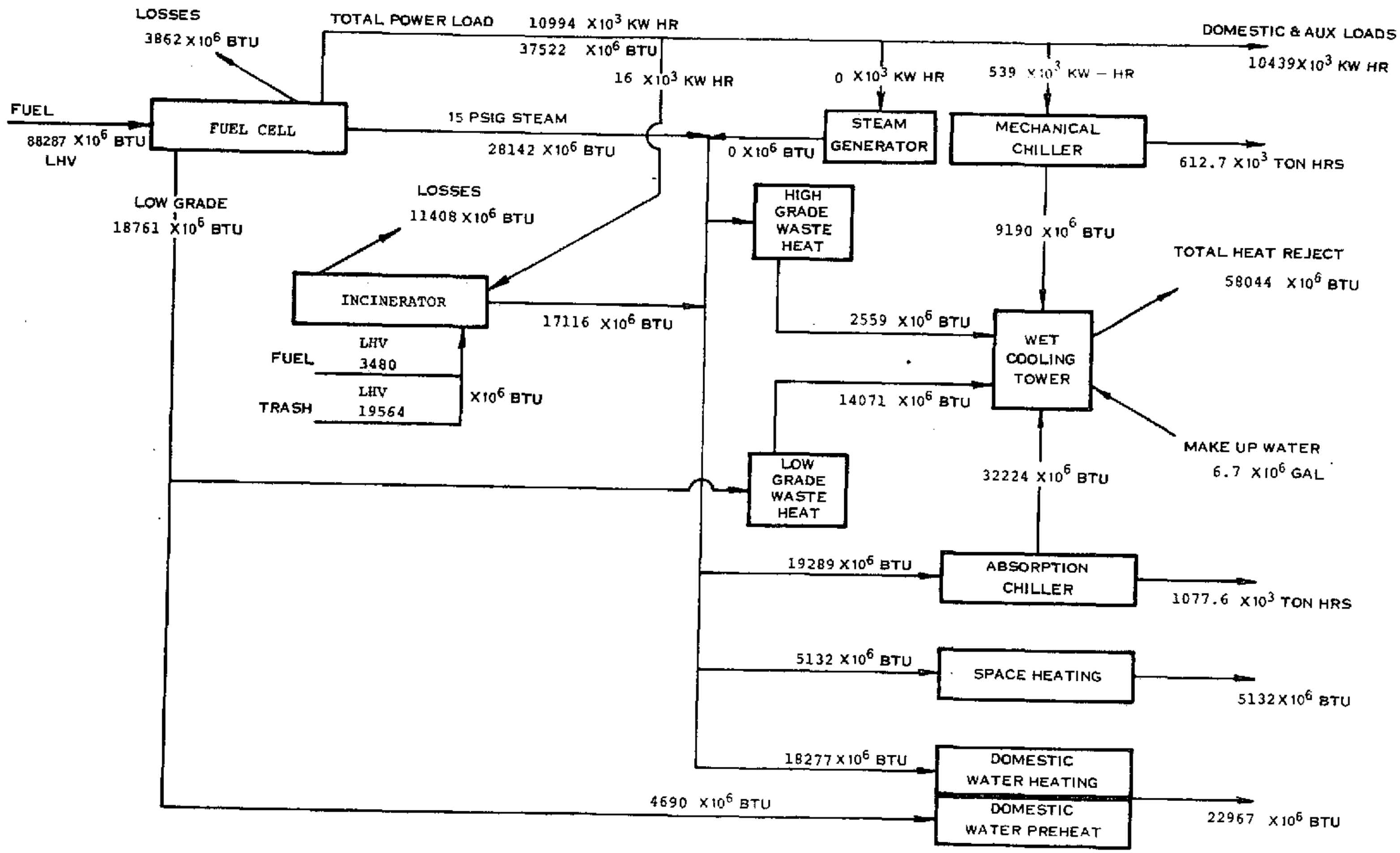
IUS - FUEL CELL - ANNUAL
NO SOLID WASTE DISPOSAL

FIGURE 8



IUS BASELINE - DIESEL - ANNUAL
WITH INCINERATION

FIGURE 9



IUS - FUEL CELL - ANNUAL
WITH INCINERATOR

FIGURE 10

6.0 (Continued)

of these cases along with the unused high-grade heat which is rejected. Table 9 presents this comparison. The incorporation of an incineration system with heat recovery is effective in the fuel cell case, but it is not effective in the diesel generator IUS. The reason is that diesels produce sufficient high-grade heat to meet most of the IUS demand. The heat recovered from the incineration system is only effective in the summer for absorption chilling.

The fuel cell, on the other hand, operates at higher electrical conversion efficiency and produces less recoverable heat. In this case the heat recovered from the incinerator is utilized more effectively throughout the year to meet the IUS demands.

TABLE 9

IUS FUEL AND WASTE HEAT COMPARISON, INCINERATION AND NO SOLID WASTE DISPOSAL

(MILLION BTU'S)

	NO SOLID WASTE DISPOSAL	INCINERATION
DIESEL GENERATORS		
ANNUAL FUEL CONSUMPTION	107,100	108,400
HIGH-GRADE HEAT REJECTED	2,313	14,565
FUEL CELLS		
ANNUAL FUEL CONSUMPTION	95,400	91,800
HIGH-GRADE HEAT REJECTED	0	2,559
HIGH-GRADE HEAT RECOVERED FROM SOLID WASTE	0	17,100

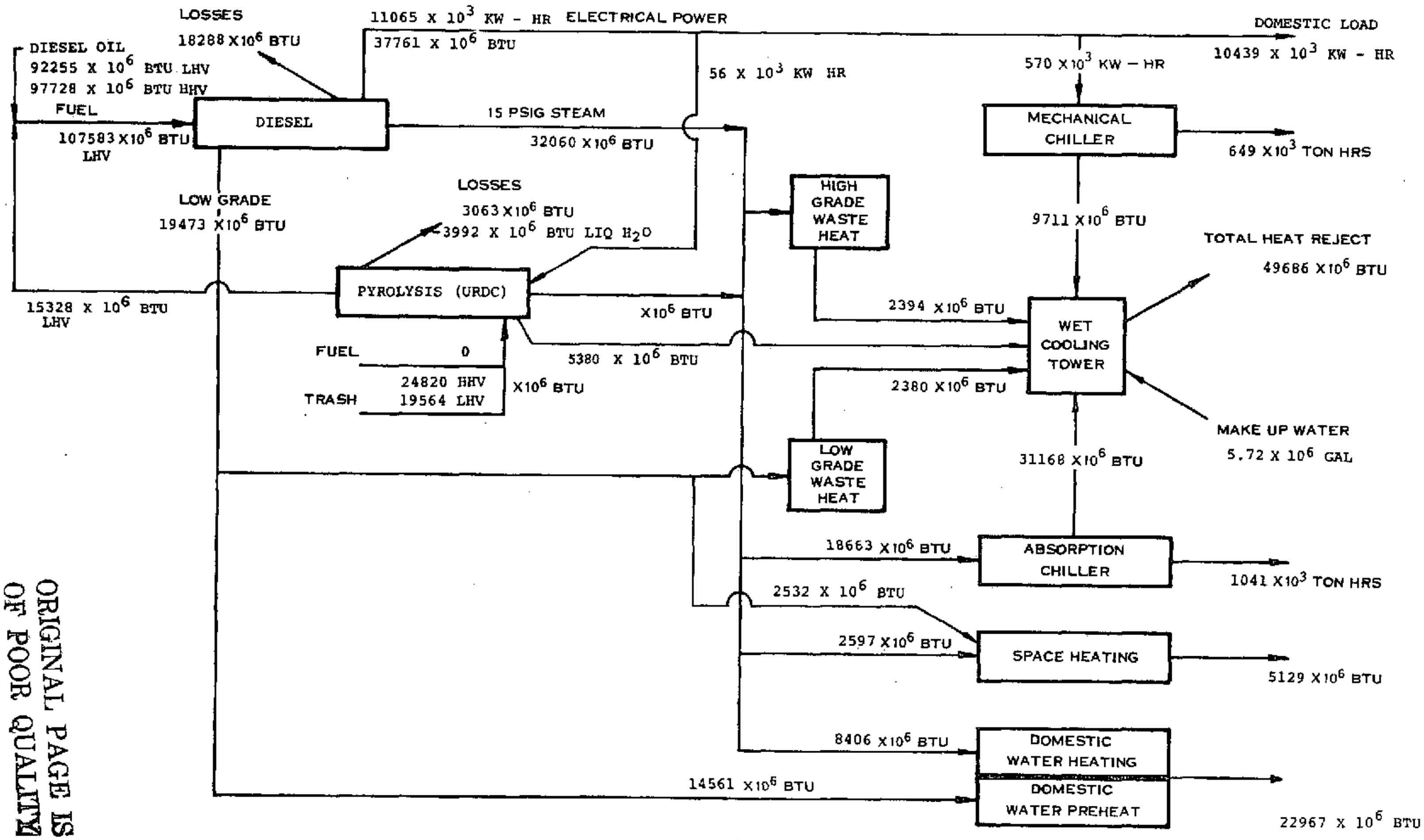
INTEGRATED PYROLYSIS/IUS SYSTEMS

The integration of pyrolysis for solid waste and sewage sludge disposal in an IUS has the advantage of recovering energy in the form of fuel which can then be used to generate electricity. Therefore, the replacement of the incineration system in the baseline IUS with the two pyrolysis concepts was investigated for its impact on IUS fuel consumption and overall energy conservation. The integration and results of this investigation are summarized in this section; details are presented in Appendices E1, E2 and E5.

The integration of the URDC pyrolysis system into the IUS was a direct substitution for the incinerator system. There is no major heat rejection from this system in useable form. Therefore, the use of pyrolysis gas as a supplementary fuel in the IUS was the only form of energy recovery considered. The integrated URDC pyrolysis system in an IUS is illustrated in Figures 11 and 12.

In the Barber Colman pyrolysis system, however, heat energy in the exhaust from the radiant tube heaters can be recovered. This heat recovery was included in the investigation along with the pyrolysis gas as supplementary fuel. The integrated Barber Colman pyrolysis system in an IUS is illustrated in Figures 13 and 14.

The annual utilization of energy is summarized in Tables 10 and 11 to the subsystem level for comparison with each other and



IUS - DIESEL - ANNUAL
WITH PYROLYSIS (URDC)

FIGURE 11

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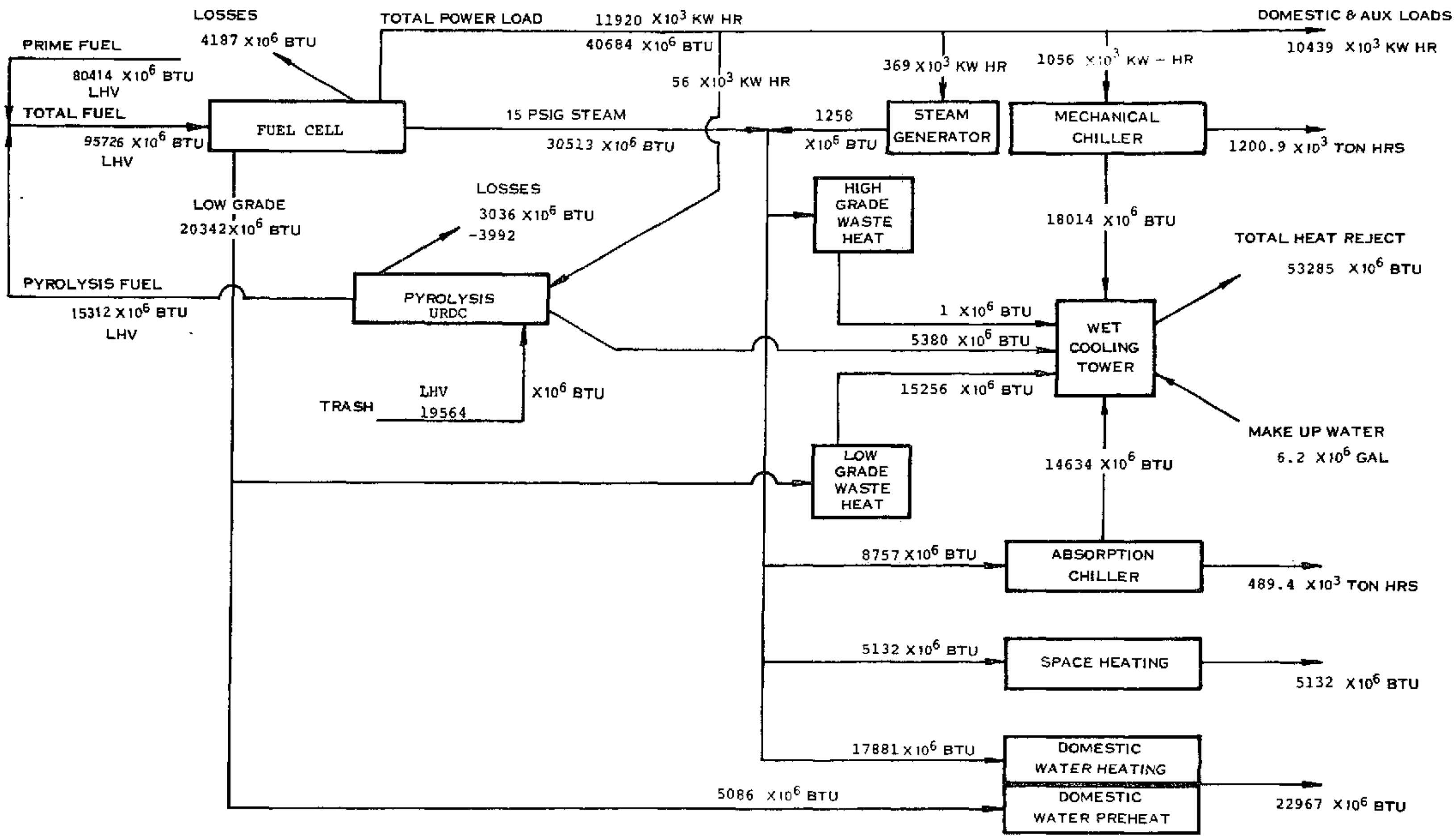
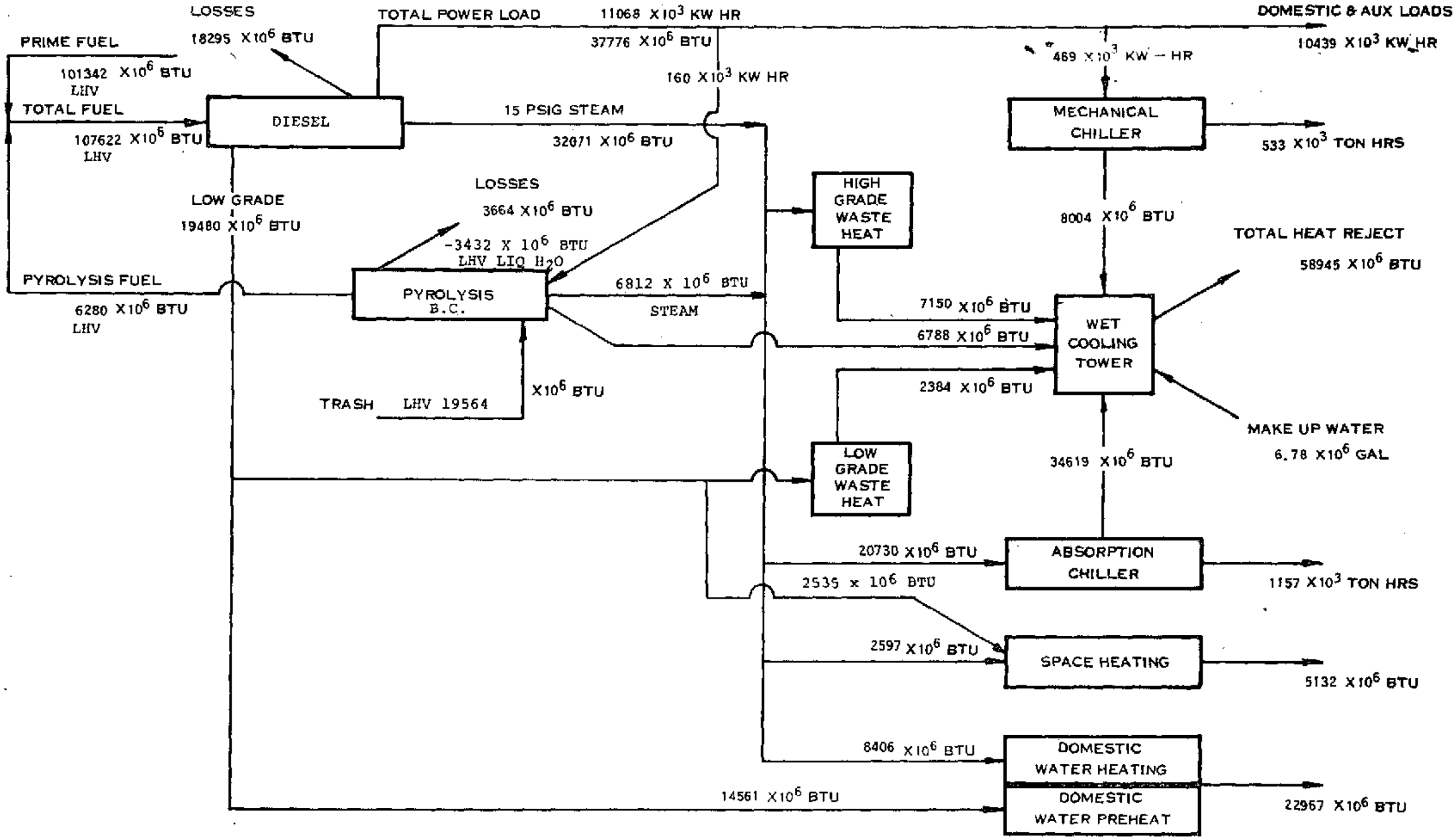


IUS - FUEL CELL - ANNUAL
WITH URDC PYROLYSIS

FIGURE 12

Hamilton Standard
DIVISION OF UNITED AIRCRAFT CORPORATION



IUS - DIESEL - ANNUAL
WITH PYROLYSIS (B.C.)

FIGURE 13

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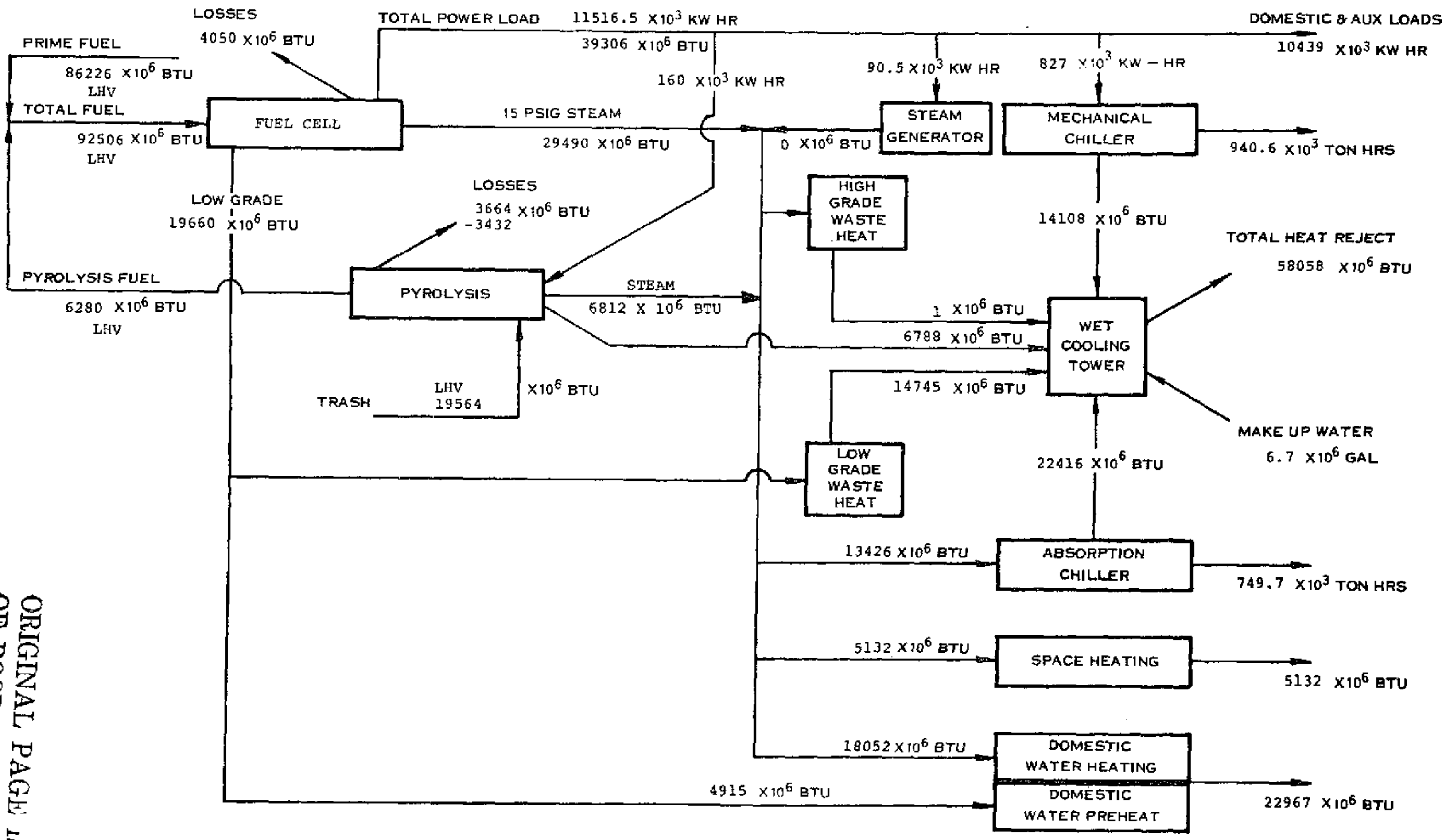


IUS - FUEL CELL - ANNUAL
WITH B. C. PYROLYSIS

FIGURE 14

TABLE 10

SUMMARY OF ANNUAL ENERGY UTILIZATION FOR DIESEL IUS

		NO SOLID WASTE DISPOSAL	INCINERATION	URDC	BARBER COLMAN
FUEL OIL CONSUMED	(10^6 BTU) LHV	107,076	108,671	92,255	101,342
PYROLYSIS FUEL GAS	(10^6 BTU) LHV	-	-	15,328	6,280
ELECTRICAL POWER	(10^3 KW-HRS)	11,012	10,818	11,065	11,068
ABSORPTION CHILLING	(10^3 TON-HRS)	1,038	1,278	1,041	1,157
COMPRESSION CHILLING	(10^3 TON-HRS)	652	412	649	533
TOTAL HIGH GRADE HEAT	(10^6 BTU)	31,909	48,562	32,060	38,883
HIGH GRADE HEAT FROM SOLID WASTE	(10^6 BTU)	0	17,116	0	6,812
HIGH GRADE HEAT REJECTED	(10^6 BTU)	2,313	14,565	2,394	7,150
TOTAL LOW GRADE HEAT	(10^6 BTU)	19,381	19,039	19,473	19,480
LOW GRADE HEAT REJECTED	(10^6 BTU)	2,288	1,939	2,380	2,384

NOTE: STARTUP FUEL FOR SOLID WASTE SYSTEMS NOT INCLUDED

TABLE 11

SUMMARY OF ANNUAL ENERGY UTILIZATION FOR FUEL CELL IUS

		NO SOLID WASTE DISPOSAL	INCINERATION	URDC	BARBER COLMAN
FUEL OIL CONSUMED	(10^6 BTU) LHV	95,374	91,767	80,414	86,226
PYROLYSIS FUEL GAS	(10^6 BTU) LHV	-	-	15,312	6,280
ELECTRICAL POWER	(10^3 KW-HRS)	11,876	10,994	11,920	11,517
ABSORPTION CHILLING	(10^3 TON-HRS)	483	1,078	489	750
COMPRESSION CHILLING	(10^3 TON-HRS)	1,207	613	1,201	941
TOTAL HIGH GRADE HEAT	(10^6 BTU)	31,679	45,258	30,513	36,393
HIGH GRADE HEAT FROM SOLID WASTE	(10^6 BTU)	-	17,116	31,771	6,812
HIGH GRADE HEAT REJECTED	(10^6 BTU)	0	2,559	0	0
TOTAL LOW GRADE HEAT	(10^6 BTU)	20,266	18,761	20,342	19,660
LOW GRADE HEAT REJECTED	(10^6 BTU)	15,199	14,071	15,256	14,745

NOTE: STARTUP FUEL FOR SOLID WASTE SYSTEMS NOT INCLUDED.

(Continued)

the baseline IUS system introduced in Section 6.0. These Tables illustrate once again that diesel generator powered IUS's have nearly sufficient high grade heat to meet demands. The recovery of additional heat from the solid waste disposal system is not, in general, very effective in conserving energy, because most of the heat is rejected to the atmosphere. In the case of fuel cell powered IUS's, the recovery of high grade heat from the solid waste system is useful, because the fuel cell system does not generate sufficient high grade heat to meet the demand. In both the diesel and fuel cell cases, the most effective energy conservation method is the use of pyrolysis fuel gas in the electrical power subsystem. Methods for the direct utilization of pyrolysis gases in diesel generators, fuel cells and other prime movers are discussed in Appendices F1, F2, and F3.

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION UA®

APPENDIX A1

URDC PYROLYSIS SYSTEM MASS AND ENERGY BALANCE

URDC PYROLYSIS SYSTEM ENERGY BALANCE

The following is a discussion of the development of the mass and energy balances presented in Hamilton Standard document, HSPC 74T07, Supplement A Section 4.0, Net Power Efficiency. This document was the Technical Supplement to Hamilton Standard's proposal bearing the same number and referenced in the Contract Statement of Work.

PYROLYSIS REACTOR MASS BALANCE

The basic mass and energy balance in HSPC 74T07 was done for an input mass flow of 500 lb refuse/hr. Gasification air requirements were taken as 1 lb air/lb refuse. This is consistent with URDC experience as can be seen from Table 1 which summarizes data from a small 140 lb/hr pilot plant. It also is consistent with Union Carbide experience on a small oxygen gasifier pilot plant (0.18 - 0.2 lb O_2/lb refuse, which would be equivalent to 0.8 - 0.9 lb air/lb refuse). There is some experimental evidence, as well as reasonable theoretical foundation, to expect the gasification air requirement to go down in larger scale systems because of their lower heat loss. However, to be conservative, the high value of 1 lb/lb was used resulting in a gasification air requirement of 500 lb/hr.

Inert content of the refuse was assumed to be 22% which is typical for average municipal refuse. The slag production therefore would be:

$$\dot{m} = (0.22)(500) = 110 \text{ lb/hr slag}$$

Table 1

URDC Performance Data

140 lb/hr Pilot Plant

Run No.	Bed Loading lb/hr-ft²	Refuse Inerts %	Gasifier Air Temp. °F	Gasifier Air/Refuse lb/lb
1	61	20.7		
2	104	35.6		
3	104	30.9		
4	96	30.9		
5	139	30.9		
6	104	30.9		
7	143	20.8		
8	86	32.8		
9	82	25.1		
10	68	25.3		
11	75	25.6		
12		24.4		
13	86	20.3		
14	68	23.6		
15	64	38.5		
16	71	30.5		
17	71	39.9		
18	79	22.6	1525	
19	61	36.9	1500	
20	57	44.4	1460	
21	59	35.5	1480	
22	64	30.4	1300	
23	82	33.9	1470	
24	79	30.5	1340	
25	79	43.0	1360	
26	83	42.4	1440	.94
27	79	33.5	1440	
28	80	28.4	1480	1.01
29	86	37.4	1470	.82
30	82	33.3	1510	
31	64	42.5	1470	
32	84	29.9	1330	1.08
33	64	18.2	1405	1.34
34	108	29.9	1450	.85
35	109	26.1	1225	.83
36	93	28.7	1100	.95
37	100	34.9	1255	.94
38	89	40.2	1300	.93
39	84	45.9	1405	.97
40	100	36.0	1260	.81

The total pyrolysis reactor off-gas flow then can be calculated by difference

$$\dot{m} = 500 + 500 - 110 = 890 \text{ lb/hr gas}$$

It should be noted that this is not the dry gas flow, nor are all the constituents necessarily in the vapor state when removed from the gasifier. That is, the off-gas contains water (vapor at normal off-gas temperatures) as well as condensable organic pyrolysis products such as tars and oils.

PYROLYSIS REACTOR HEAT BALANCE

Heat balance calculations were done on an HHV basis. This was done because it is almost universal U.S. practice in specifying fuels or fuel using equipment to base specifications on HHV rather than LHV. For many purposes an LHV basis is much more meaningful, especially when wet fuels are being studied. However for the purposes of estimating the efficiency of a close-coupled system, differences between the two approaches are not significant. Furthermore, use of the HHV basis allows easy comparison of results to literature values.

A refuse HHV of 5,000 Btu/lb was assumed giving an input of 2.5 X 10^6 Btu/hr.

A gasification air temperature of 1400°F was assumed. Again this is typical of URDC pilot plant experience. Taking a 60°F

assumed. An internal L/D of 3 was chosen to give the height of the basic gasifier. An 8" wall thickness and 12" floor thickness was used to give an estimated total gasifier outside surface area of 150 ft^2 (wall + floor). Since incoming refuse flows down through the upper crossection, any upward heat flow is not lost from the system. Any gasifier surface area above the processing section (for example such as the part of the gasifier volume used simply as internal holding volume)is not in contact with the hot products and therefore would have insignificant heat loss. The hot surface area then was arbitrarily increased by 25% to allow for all other system heat losses. The average surface temperature over the entire hot surface was assumed to be 80°F above ambient. A 5 MPH breeze was assumed. This gives a Q/A - 310 Btu/hr - ft^2, and the total estimated heat loss becomes:

$$\dot{Q} = (150)(1.25)(310) \approx 60{,}000 \text{ Btu/hr}$$

Note that the hot zone within the gasifier, where relatively high outside surface temperatures would be expected, takes up only a small part of the total gas processing volume. Furthermore, no heat credit has been taken for the electrical power input. (i.e. A major part of the electrical power goes to blowers and will show up as sensible heat in the air. This sensible heat is recoverable by the system.)

Since there are no other energy fluxes associated with the gasifier, the net heating value in the fuel gas produced must be:

reference temperature, the heat input into the reactor associated with the sensible heat in the gasification air is:

$$\dot{H} = (500)(.25)(1400-60) \approx 170{,}000 \text{ Btu/hr}$$

Heat losses associated with the removal of the molten slag from the gasifier were estimated on a very conservative basis. Slag temperature was taken as 2400°F which is somewhat higher than the usual slag temperature at the point of tapping. A mean specific heat of 0.27 was used. This is representative of glass for the temperature range involved. Since glass is not a crystalline solid, no heat of fusion is involved. Since the slag is tapped as a single oxide phase, this value was used for the entire mass. This is conservative since the specific heat of the other constituents tends to be lower, even allowing for the heat of fusion. For example, the approximate average heat capacity of iron, the other major constituent of the inerts, including the heat of fusion, is only about 0.2. The resultant heat flux associated with the slag tap is:

$$\dot{H} = (0.27)(2400-60)(110) \approx 70{,}000 \text{ Btu/hr}$$

Heat losses to ambient also were calculated on a conservative basis. Since the gasifier is the largest piece of hot hardware, all heat losses were arbitrarily assigned to it. The calculation basis is as follows. For 500 lb/hr a gasifier ID on a normal design basis would be about 2.5 ft. However, to accommodate ordinary mixed refuse without shredding, a 3' ID gasifier was

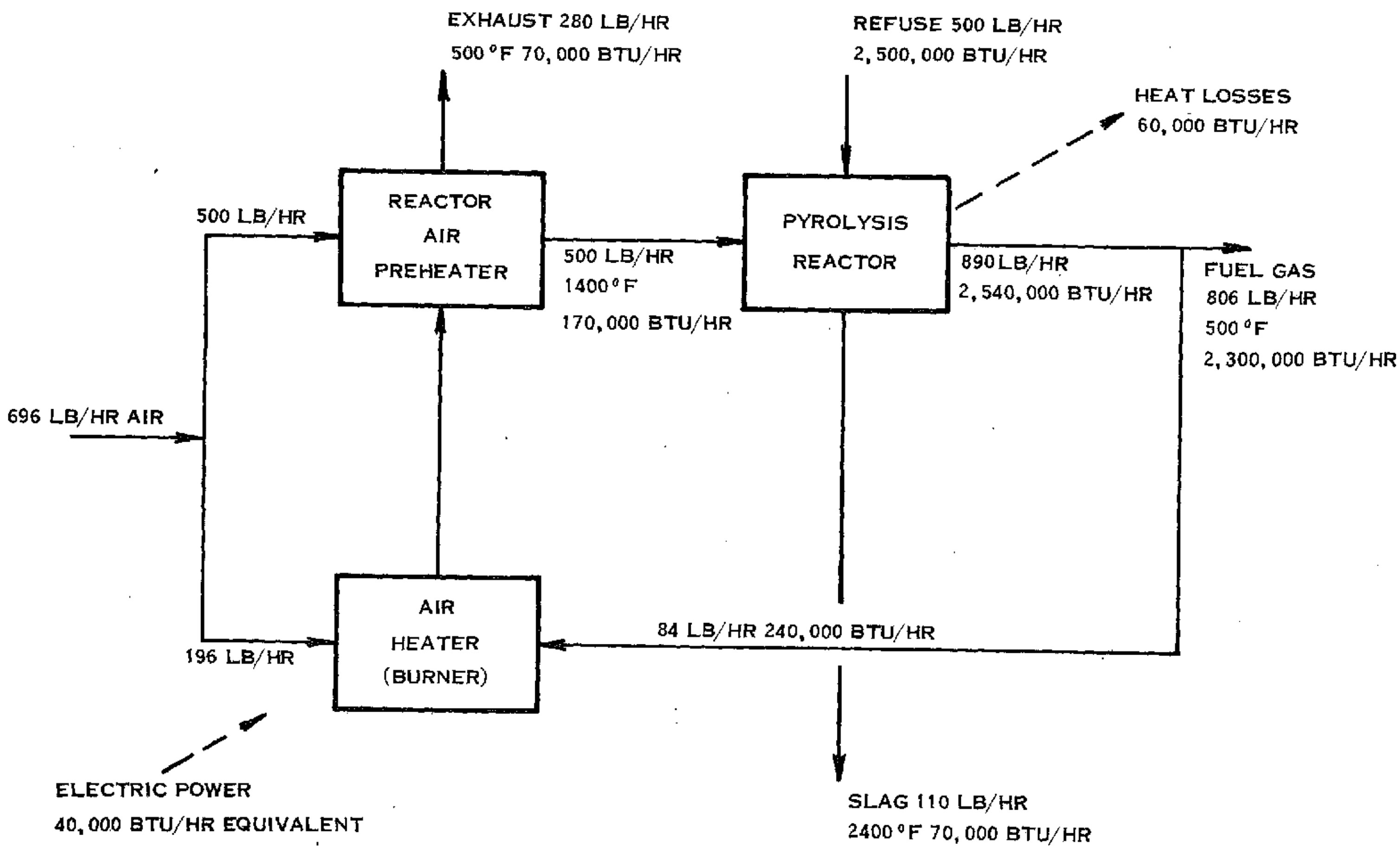
$$\dot{HHV} = 2{,}500{,}000 + 170{,}000 - 70{,}000 - 60{,}000 = 2{,}540{,}000 \text{ Btu/hr}$$

Note that this is not the cold gas heating value but rather the effective HHV that would be delivered to a close coupled fuel burning system such as a boiler. The bulk of the total heating value is in the heat of combustion of the dry gas plus condensable organics (tars and oils). A small fraction of the total energy is in the sensible heat of the fuel gas. Since the calculations are done on an HHV basis the heat of vaporization of water in the fuel gas also must be counted as part of the total heating value.

URDC SYSTEM, HOT GAS EFFICIENCY

Part of the gasifier product must be consumed in order to heat the gasification air. In rechecking the calculations made around the gasification air heating subsystem, two errors were found. One was in the mass flow calculation. The other error was that the heat of vaporization of water in the hot side exhaust from the air heater was neglected. A corrected calculation is presented as follows and a corrected heat and mass balance is given in Figure 1.

To simplify heat exchanger design and control, and to insure adequate life, it was assumed that the fuel gas in the air heater burner would be burned with enough excess air to reduce the flame temperature to 2500°F. If we further assume that the air to be heated will be delivered from a blower at 100°F, and that the heat



$$\eta = \frac{2,300,000 - 40,000}{2,500,000} = 90\%$$

URDC PYROLYSIS HOT GAS EFFICIENCY
FIGURE 1

exchanger has adequate surface to give a hot side exhaust temperature of 500°F, then the required heat exchanger effectiveness becomes:

$$E = \frac{2500^{\circ}F - 500^{\circ}F}{2500^{\circ}F - 100^{\circ}F} = 83\%$$

This is achievable with counterflow or counterflow/crossflow heat exchangers, especially since the heat capacity ratio works out to be well under 1.

The heat capacity of the hot side exhaust was taken as 0.28 to account for the high water vapor content. The heat capacity of the same stream through the elevated temperature range of the heat exchanger (2500 - 500°F) was correspondingly taken as 0.30. Since the heat gain by the air is equal to the heat lost by the combustion products the combustion product mass flow can be calculated as follows:

$$\dot{m} = \frac{(170{,}000\ \text{Btu/hr})}{(0.3\ \frac{\text{Btu}}{\text{hr}^{\circ}\text{F}}\ \ (2500-500^{\circ}\text{F})} \approx 280\ \text{lb/hr}$$

The exhaust sensible heat loss is:

$$\dot{H} = (280)(.28)(500-60) \approx 35{,}000\ \text{Btu/hr}$$

The heat of vaporization of the water vapor in the exhaust represents approximately 15% of the input HHV for the wet fuel gas plus water resulting from combustion.

$$\dot{HHV} = 35,000 + (0.15)(\dot{HHV}) + 170,000$$

$$\dot{HHV} \approx 240,000 \text{ Btu/hr}$$

The exhaust loss then becomes:

$$\dot{H} = 240,000 - 170,000 = 70,000 \text{ Btu/hr}$$

The fuel and air flow to the burner then can be calculated. The fuel flow is:

$$\dot{m} = (890)\frac{(240,000)}{(2,540,000)} = 84 \text{ lb/hr}$$

The air flow is:

$$\dot{m} = 280-84 = 196 \text{ lb/hr}$$

This gives an air/fuel ratio of well over stoichiometric as expected.

The resultant efficiency of the air heater subsystem is:

$$N = \frac{170,000}{240,000} = 71\%$$

This is a reasonable value considering that commercial boilers easily can achieve 80% efficiency firing natural gas, which would be equivalent to 75% on fuel gas with its higher exhaust water

content. The net mass and energy flow available from the fuel gas then becomes:

$$\dot{m} = 890 - 84 = 806 \text{ lb/hr}$$

$$\dot{HHV} = 2{,}540{,}000-240{,}000 = 2{,}300{,}000 \text{ Btu/hr}$$

The system efficiency, on a HHV basis, and not including electrical power consumption becomes:

$$N = \frac{2{,}300{,}000}{2{,}500{,}000} = 92\%$$

The electric power consumption was estimated as follows:

hot gas blower (494 cfm @ 6")	846 watts
gas burner blower (43 cfm @ 3")	37 watts
gasification air blower (110 cfm @ 20")	629 watts
refuse conveyor	373 watts
ram feed	373 watts
instruments and controls	1000 watts
miscellaneous	742 watts
total	4000 watts

Since electrical power is more valuable from an energy standpoint than fuel heating value, an equivalent heating value had to be calculated. A typical heat rate of 10,000 Btu/kwh was used giving a total equivalent electrical consumption of:

$$Q = (4kw)(10{,}000\ \frac{Btu}{kwh}) = 40{,}000\ Btu/hr$$

The over-all system efficiency, still on an HHV basis, but including electrical power then becomes:

$$N = \frac{2{,}300{,}000}{2{,}500{,}000+40{,}000} = 91\%$$

Alternatively the electric power could be charged to the fuel gas output rather than added to the energy input. This would give:

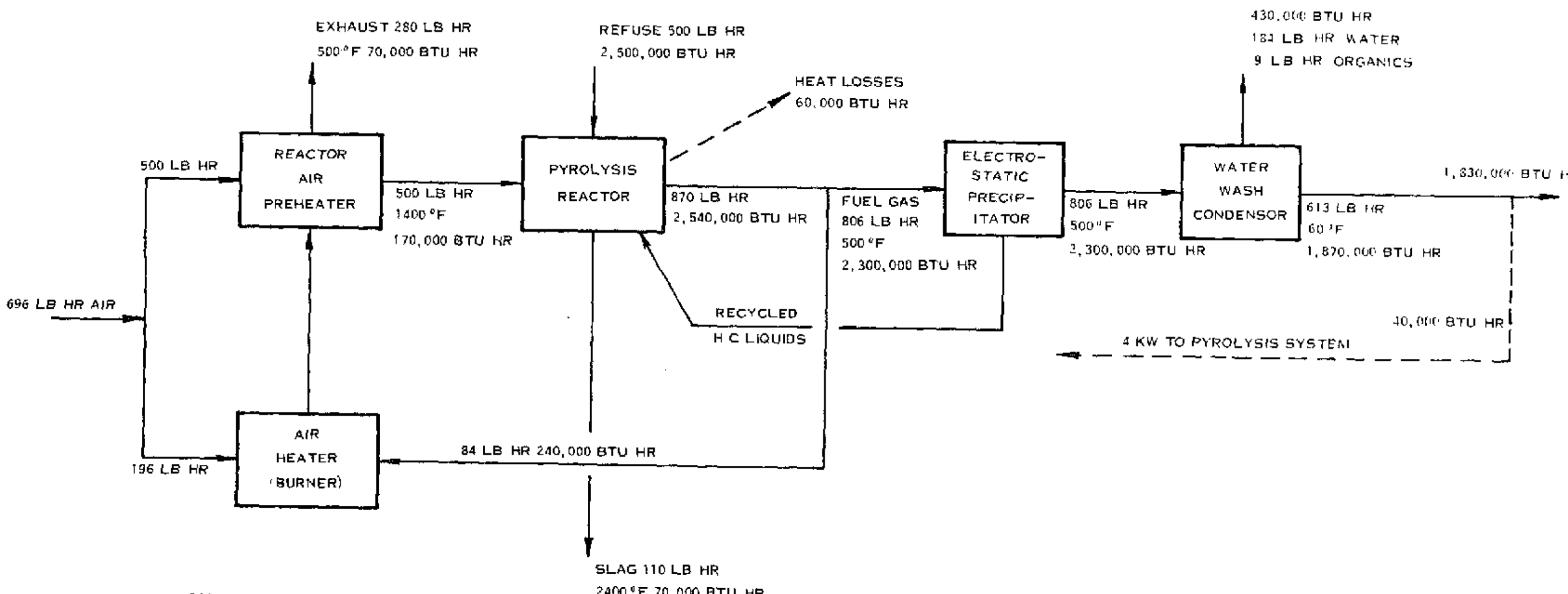
$$N = \frac{2{,}300{,}000-40{,}000}{2{,}500{,}000} = 90\%$$

It also could be argued that 5,000 Btu/lb is too high and HHV for typical refuse, and that 4500 Btu/lb would be more reasonable. On this basis the efficiency becomes:

$$N = \frac{2{,}050{,}000-40{,}000}{2{,}250{,}000} = 89\%$$

COLD GAS EFFICIENCY

Figure 2 shows the URDC system efficiency on a cold gas basis. The bulk of the condensable hydrocarbons are recycled to the gasifier increasing the gas mass flow leaving the gasifier, but giving the same fuel gas flow as previously calculated at the exit of the precipitator. For convenience the entire cooling step was taken at the condenser. It was assumed that the initial refuse contained 25% water and 21% O_2. It was further assumed that 1/2 of the O_2 would go to water in the pyrolysis process. Thus the total water becomes:



COLD GAS EFFICIENCY, HHV BASIS

$$\eta = \frac{1,830,000}{2,500,000} = 73\%$$

URDC PYROLYSIS COLD GAS EFFICIENCY
FIGURE 2

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refuse water = .25 X 500 = 125

formed water = $.21 \times \frac{18 \text{ lb } H_2O}{16 \text{ lb } O_2} \times 1/2 \times 500 =$ 59

184 lb/hr H_2O

It was assumed that the water would carry away 5% organic liquids (9 lb/hr) at 14,000 Btu/hr. The total losses in going from hot raw fuel gas to cold clean gas then becomes:

sensible heat	= (806)(.31)(500-60)	≈ 110,000 Btu/hr
lost organic liquids	= (9)(14,000)	= 126,000 Btu/hr
latent heat of water	= (184)(1060)	≈ 195,000
		431,000 Btu/hr

The net available HHV in the cold fuel gas, after allowance for electric power consumption becomes:

$$\dot{HHV} = 2{,}300{,}000 - 430{,}000 - 40{,}000 = 1{,}830{,}000$$

The efficiency on a cold gas HHV basis but including all losses and electric power then becomes:

$$N = \frac{1{,}830{,}000}{2{,}500{,}000} = 73\%$$

It should be noted that on a LHV basis the efficiency based on warm raw gas would be a little lower, but the cold gas efficiency would be significantly higher. (i.e. On a LHV basis the water vapor loss is charged to the fuel and not the fuel using process. On a HHV basis the loss is charged to the boiler or other fuel gas using process if the system is close coupled, and to the gasi-

fier if the system uses cold gas.)

COMPARISON TO OTHER SYSTEMS

The similarities between coal fired gas producers and refuse fired fixed bed gasifiers have been discussed in a previous draft ("Pyrolysis Gas Confirmation"). Therefore, it is instructive to compare typical efficiencies for gas producers with the above results. The following quote from Reference 2 gives typical gas producer efficiencies as: "The efficiency of conversion, per cent total calorific value of fuel recovered, is 88-90% when raw gas is consumed hot, and 65-80% when the gas is cooled and cleaned." McDonald Wellman Engineering Company (manufacturer of Wellman gas producers) states that efficiencies up to 93% can be obtained. Reference 3 gives the efficiency of modern gas producers as "90 or even 95%, referred to the hot gas". The efficiency for clean producer gas, with no recovery of energy from tars and sensible heat, is given as about 70%. Trinks (Ref. 3) states that, "in the 1920's clean producer gas was considered to be the most suitable fuel for scattered furnaces in an industrial establishment." It has largely been replaced by natural gas and by electric energy in the U.S.

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2. Anonymous, The Making, Shaping and Treating of Steel, United States Steel Corporation, Pittsburgh, Pa., 1957.
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APPENDIX A2

URDC PYROLYSIS SYSTEM GAS COMPOSITION AND HEATING VALUE

URDC PYROLYSIS SYSTEM GAS COMPOSITION AND HEATING VALUE

INTRODUCTION

The gas compositions given on page 27 of HSPC 74T07 were obtained by modifying the available URDC data as necessary to satisfy a detailed heat and mass balance for a refuse input typical of average municipal refuse. The calculation requires the assumption of a refuse composition and heating value as well as certain pyrolysis parameters.

Since a rather time consuming trial and error calculation is involved, and since the time available to prepare HSPC 74T07 was quite short, an available analysis was used. This analysis had been done some time ago to enable calculation of fuel gas properties for a paper published at the last Incinerator Conference (1).

A recent, more critical evaluation of the literature data on pyrolysis indicates that some of the assumptions made in that calculation were questionable. Particularly, the Bureau of Mines' pyrolysis tests do not appear to represent pure pyrolysis. That is, the most rational explanation for some of the effects obtained, as well as some of the differences between the Bureau of Mines data and other experiments in the literature, is that significant gas/gas and gas/solid reactions took place. This would not be unexpected from consideration of the apparatus size

and the time scales involved in the experiment. As a result the assumed amount of condensable organics probably is too low.

The water formation assumed probably also is too low. This assumption was based on a test at URDC designed to measure total condensate formation. This test indicated relatively little water formation. However, the preponderant evidence in the literature suggests that considerable water is formed. In view of the crudeness of the URDC test we would have to assume that the higher values derived through the literature are more reliable and should be used. In any case, the assumptions made do not have a very great effect on fuel gas properties or system performance. Since gas composition measurements generally are done on a dry gas basis, and since in most cases water contents are either not measured or not reported, the most convenient and least confusing way to treat composition data is strictly on a dry gas basis. This approach will be taken in the following discussion.

URDC DATA

Most of the detailed performance data available on the URDC system was obtained in a series of tests on a 140 lb/hr pilot plant operated from February to October, 1971. This program, and some of the results from it are given in Ref. 2. The main thrust of the program was to obtain data necessary to design full scale systems for either disposal applications or energy recovery with the gasifier close coupled to the fuel user. Therefore, detailed

gas composition data was not needed and took a relatively low priority. Furthermore, a really meaningful fuel gas analysis would require knowledge of the water content and condensable organic content and heating value as well as simply the noncondensable gas composition. This level of measurement was far beyond the available time, money and manpower resources.

A series of composition measurements were made. Their purpose was to shed light on the gasification process as well as to define the fuel gas. To this end, samples were taken from different points within the gasifier as well as from the fuel gas. Two gas analysis instruments were used, a simple Orsat (CO, CO_2, O_2) and a combustion Orsat (CO, CO_2, O_2, illuminants, CH_4, and H_2).

An examination of the data from these measurements made it apparent that there were some large errors. H_2 and CH_4 were very low and the unaccounted for difference (which should have been essentially N_2) was unreasonably high. A detailed examination of the specified procedures indicates that for the anticipated range of consumption the amount of air dilution before explosion and reabsorption in the Orsat system was high enough to put the composition below the lean flammability limit. As a result, the H_2 and CH_4 to be measured were only partly reacted -- if at all -- and most of them were lost from the analysis. This effect did not seem to be nearly as severe for the measurements made on gas taken from the gasifier where CH_4 levels could very conceivably

be negligible. An attempt was made to change the procedure to eliminate this problem. However, by the time this could be done the program was almost to an end and the time was not available.

The available measurements are summarized in Table 1. If we make the conservative assumption that the composition measurements for the gas taken from low in the gasifier are nearly correct, then the unaccounted for gas should be N_2. The composition should essentially be that of the fuel gas produced by char gasification only. The total fuel gas would be the char gasification product diluted by pure pyrolysis product. The net fuel gas therefore should have a lower N_2 dilution and a higher HHV than the simple char gasification product.

The two available measurements give heating values of 102 and 111 Btu/ft^3 which would be in the right magnitude for the simple char gasification product and reasonably consistent with the 150 Btu/ft^3 or so that we would expect for the total fuel gas. It should be noted that some H_2 and CH_4 may well have been lost from these measurements as well as from the fuel gas composition measurements so that the actual dilution for the char gasification product would be lower than that measured and the actual heating values somewhat higher.

OTHER DATA

The most reliable published data on fixed bed gasification of

Table I

URDC Gas Analysis

DATE/LOCATION	5/25/71 Gasifier Hot Zone	5/25/71 Gasifier Hot Zone	5/25/71 Fuel Gas	5/26/71 Fuel Gas	5/26/71 Fuel Gas
CO_2	2.6	1.1	14.0	14.7	13.4
illuminants	0	0	0.7	2.0	0.9
O_2	4.6	3.1	1.7	1.3	0.9
CO	26.0	23.3	10.4	10.9	10.3
CH_4 [1,2]	0	0	1.1	1.0	0
H_2 [2]	6.6	13.2	2.2	2.7	4.2
Difference[3]	60.2	59.3	69.9	68.4	70.3
HHV[4]	102	111			

NOTES:
1. Assumes all hydrocarbons except illuminants are CH_4
2. Probably both CH_4 and H_2 are significantly low for almost all cases because of limitations of experimental technique
3. Difference = N_2 + lost CH_4 + Lost H_2
4. Only calc. for samples taken from the gasifier hot zone since these are the only samples for which the difference could be reasonably taken as N_2

CQ

Table 1
(continued)

URDC Gas Analysis - continued

DATE/LOCATION	6/2/71 Fuel Gas	6/2/71 Fuel Gas	6/2/71 Fuel Gas	6/2/71 Fuel Gas	6/2/71 Fuel Gas	6/3/71 Fuel Gas	6/3/71 Fuel Gas	8/11/71 Fuel Gas	8/11/71 Fuel Gas
CO_2	12.9	12.9	13.4	13.1	8.9	14.4	12.9	16.0	16.0
illuminants	0.7	1.7	0.9	1.6	1.7	1.3	1.6	1.1	1.1
O_2	0.7	1.4	0.1	3.0	0.9	1.1	1.0	1.3	1.3
CO	11.4	12.1	12.3	8.6	20.7	8.1	9.3	3.7	3.7
CH_4	0	0	0.4	1.1	0.3	0.4	0.4	1.5	1.5
H_2	2.5	2.6	2.6	.5	2.8	2.0	2.2	1.1	7.9
Difference	71.8	69.2	70.3	71.1	64.4	72.7	72.8	75.3	68.5
(HHV)				(85)	(120)				

solid wastes is the Union Carbide data for their oxygen gasifier (3). The gasification behavior of an O_2 gasifier and a gasifier using heated air is basically quite similar as evidenced by the essentially identical gasifier oxygen demands. The data for the Union Carbide O_2 gasifier was converted to the equivalent air gasifier product by two methods as outlined in the Attachment. The results are given in Table 2. The best value for the air gasifier product HHV probably is 143 Btu/ft^3 which is well within the expected range.

The fixed bed gasifier for refuse is quite similar in basic nature to gas producers used to make producer gas from coal. These gasifiers generally use air or air/steam, and operate at non-slagging conditions and atomospheric pressure. Mechanical grates are required for ash removal. Gas producers, though once very common, went out of fashion with the advent of very low-cost natural gas. However, interest is being revived because of the energy shortage and the basic interest in coal gasification (4). Their major limitation is the operational problem of dealing with caking coals. Quoting from the introduction of Ref. 5, which deals with recent Bureau of Mines experimental work with fixed bed coal gasifiers, "Low-Btu fuel gas from coal could be used for power generation as replacement for natural gas or fuel oil. Probably the least complicated system for converting coal into low-Btu fuel gas is to gasify it in a fixed bed using air and steam. Historically, the fixed-bed gas producer has required a feed of

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Table 2

Union Carbide Gas Analysis

	Published O_2 Gasifier Data	O_2 Gasifier Data corrected to Air Gasification Assum.A	Assum.B	Unpublished Air Gasifier Data
CO_2	14.8	6.7	7.4	8
C2's	1.8	0.8	1.0	0.5
O_2	0.0	0.0	0.0	0
CO	53.2	24.1	26.6	24
CH_4	3.1	1.4	1.6	2
H_2	26.4	12.0	13.2	14.5
N_2	0.6	55.0	50.3	51
HHV	309	143	159	154

non-caking lump-size coal or coke in order to insure continuous operation." This limit, of course, does not exist with refuse feeds.

From a thermodynamic performance standpoint, the difference between coal gasification and refuse gasification is largely tied to difference in volatile content, ash content, and water content. In coal gasification, particularly with coke breeze or anthracite as the feed, the gasification process is almost exclusively one of the gasification of char by partial oxidation since the feedstock volatile content is so low. With refuse, char gasification is a much smaller portion of the over-all process and pyrolysis of the volatiles a much larger one. Since pyrolysis is driven by the heat remaining from char gasification --which otherwise would not be recoverable except as sensible heat--the fixed bed process tends to get better in thermal performance as volatiles make up a higher proportion of the feed. A measure of this is the off-gas temperature which tends to be considerably lower for refuse than for coal derived producer gas.

Ash content is highly variable for coal as well as for refuse but does not have a major effect on thermodynamic performance. Within reasonably wide limits for an air refuse gasifier, changes in moisture in the refuse do not have a significant effect on the gasification process as such. This is because the vaporization of the water contained in the refuse is done by the sensible

heat in the fuel gas leaving the pyrolysis zone. As refuse water levels increase, the fuel gas temperatures will drop (until saturation is reached). Thus increasing refuse water content results in a loss of energy in a close coupled system (that otherwise could make use of the sensible heat in the fuel gas) but does not cause a significant change in fuel characteristics or available energy in a system where the fuel gas is scrubbed before use.

Typical producer gas data is given in Table 3. The data were taken directly from Ref. 6. Note the increase in CH_4, illuminants, and heating value in going from coke or anthracite to the higher volatile bituminous coal.

Ref. 6 gives a range of 170-190 Btu/ft^3 for the heating value of a producer gas made from a high volatile coal if the condensable organics are included. Another set of typical composition values for producer gas were taken from Ref. 7 for a Wellman-Galusha producer.

Operating conditions for the refuse gasifier and the coal fired gas producer are fairly similar, although the gasification rates are much milder for the refuse gasification systems. That is, typical producer loadings are 50-75 lb/hr - ft^2 with bituminous coal and about half of that for coke breeze. Considering that char gasification is the limiting factor, the design bed loading

Table 3

Typical Producer Gas

	from "making, shaping & treating of steel"					for Wellman-Galusha producer			
	Coke Lump	Coke Breeze	Anthracite	Bituminous A	Bituminous B	Coke	Charcoal	Anthracite	Bituminous
CO_2	9.2	8.7	6.3	3.4	9.2	3.5	3.0	5.0	3.4
illuminants	0.1	0.0	0.0	0.8	0.4				
O_2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CO	21.9	23.3	25.0	25.3	20.9	29.0	29.5	27.1	28.6
CH_4	0.2	0.4	0.5	3.1	1.9	0.7	0.5	0.5	2.7
H_2	11.1	12.8	14.2	9.2	15.6	10.0	12.0	16.6	15.0
N_2	57.5	54.8	54.0	58.2	52.0	56.8	55.0	50.8	50.3
HHV	121	131	132	155	156	133	139	146	168

being used for the IUS system of 100 lb/hr - ft^2 is equivalent to only 7 lb/hr - ft^2 of fixed carbon gasification for typical refuse.

Theoretical flame temperature for typical producer gas is given as 3175°F (4). Although this is not as high as the flame temperature for a conventional fuel such as natural gas, LP gas, or liquid petroleum products, neither is it drastically lower. It certainly places the producer gas well within the flammability range where normal combustion equipment can be used without any unusual problems. If a fuel gas is diluted into the class of blast-furnace gas [90 Btu/ft^3, 2650°F theoretical flame temperature (4)] combustion problems can become quite severe since even under stoichiometric and adiabatic conditions the flame will be very close to the basic flammability limits.

Experience with the fuel gas produced in the rather small -- and therefore relatively high heat loss -- 140 lb/hr URDC pilot plant certainly indicated that the fuel gas would burn stably in quite conventional, and crude, gas burners without piloting or any other special requirements. The major difference in combustion characteristics is that the gas, when burned in the raw state, burns with a luminous flame due to the condensed organics it contains. The scrubbed gas can be expected to burn with a non-luminous flame quite similar to natural or other clean manufactured gases.

ESTIMATED FUEL GAS COMPOSITION

Our present best estimates of the fuel gas composition for a fixed bed gasifier of the URDC type is given in Table 4. Note that although there can be considerable swings in the level of certain constituents (e.g. CO and CO_2) all available evidence indicates that the level of certain other constituents (particularly N_2) and the HHV will stay relatively constant.

Table 4

Estimated - Fixed Bed Refuse Gasifier (URDC)

	Range	Expected
CO_2	5-16	12
illuminants	0.5-2	1.5
O_2	0-1.5	0.5
CO	8-26	18
CH_4	1-3	2
H_2	10-15	14
N_2	45-60	52
HHV	130-170	150

REFERENCES

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3. Anderson, J. E., "The Oxygen Refuse Converter," Proceedings 1974 National Incinerator Conference, ASME, New York, 1974.

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6. Anonymous, The Making, Shaping and Treating of Steel, 7th edition, U.S. Steel, Pittsburgh, Pa., 1957.

7. Anonymous, Wellman-Galusha Gas Producers, McDowell Wellman Engineering Company, Cleveland, Ohio.

ATTACHMENT

Conversion of O_2 gasifier data to air gasification

Assumptions - method (A)

1. Refuse composition: 25% inerts
   25% water
   50% burnable

2. Gasified O_2 demand the same for O_2 gasification and air gasification. This is consistent with all experimental data.

3. Gasifier O_2 demand = 0.19 lb O_2/lb refuse (U.C. data for the given gas composition; feed was typical refuse).

4. Condensable organics calc. as follows -

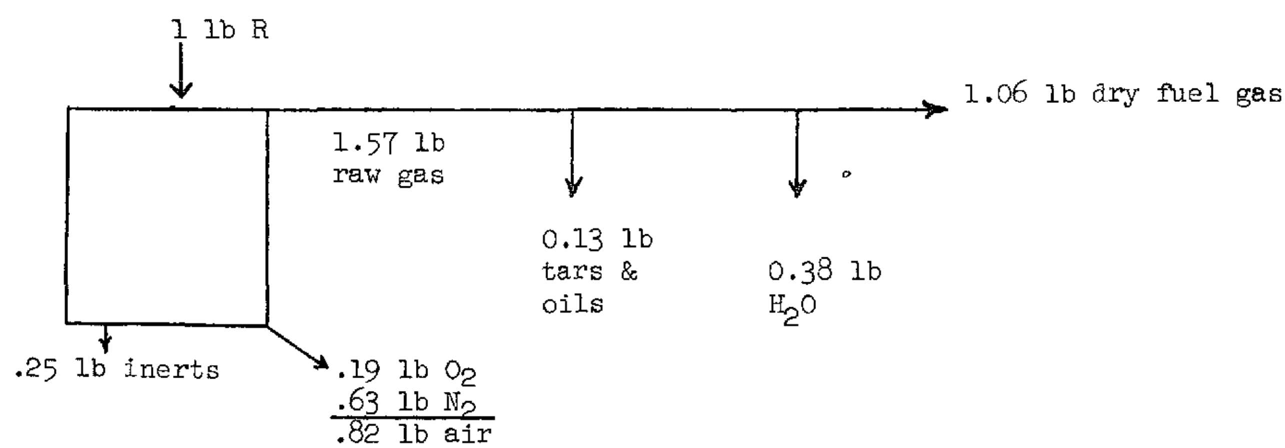
   burnable fraction of feed is 87% volatile (13% fixed carbon)

   0.31 lb cond. org./lb volatiles (Kaiser data)

$$\text{cond. organ.} = 0.5\ \frac{\text{lb b}}{\text{lb R}} \times 0.87\ \frac{\text{lb mol.}}{\text{lb b}} \times 0.31\ \frac{\text{lb C.O.}}{\text{lb mol.}} = 0.13\ \text{lb C.O./lb R}$$

5. Total water in fuel gas = 90 gal/ton refuse

$$\frac{90 \times 8.34}{2000} = 0.38\ \text{lb } H_2O/\text{lb R}$$



6. Mols N_2 added per 100 mols O_2 gasifier product

$$23.1\ \frac{\text{lb } N_2 \text{ free gas}}{\text{mol } N_2 \text{ free gas}} \times \frac{\text{lb R}}{.43\ \text{lb } N_2 \text{ free gas}} \times .63\ \frac{MN_2}{\text{lbR}} \times \frac{\text{mol } N_2}{28\ \text{lb } N_2} = 1.21\ \frac{\text{mol } N_2}{\text{mol } N_2 \text{ free gas}}$$

where 23.1 is avg. molec. wt. of gas. prod.

Assumptions - method (B)

An arbitrary 50% N_2 was added to the O_2 gas. prod. (i.e. 100 mol N_2 were added per 100 mol O_2 gas. prod.)

APPENDIX A3

BARBER COLMAN PYROLYSIS SYSTEM GAS CONFIRMATION

BARBER COLMAN PYROLYSIS SYSTEM GAS CONFIRMATION

The following is a discussion of the Barber-Colman gas composition data as provided by the NASA.

Table 1 is a summary of the gas compositions and heating values provided for the Barber-Colman system. Also shown are literature values for comparison. The Kaiser data (1) was obtained with a small batch retort which allowed sufficiently high heat transfer rates to maintain the batch at a constant temperature throughout. Pyrolysis was relatively rapid with times on the order of minutes to an hour. Since there was little time or opportunity for gas/gas or gas/solid reactions, this data can be taken to be representative of the pure pyrolysis process.

The San Diego work (2) was done with two sizes of retorts, 4" diameter and an 18" diameter. Heat transfer rates from the retort wall through the 18" diameter refuse bed could be expected to be quite slow and this is shown by the results. That is, gasification required a very long time (the 5 - 10 hour range). As a result there was considerable opportunity for gas/gas and gas/solid reactions. For example water formed in one section of the retort could react with char previously formed in some other section; vapor phase water and tars flowing through the hot zone could also react with each other. The results indicate that these effects were serious enough to have a considerable influence on

Table 1

Summary of Pyrolysis Gas Composition Data

	BARBER-COLMAN			KAISER		SAN DIEGO		BUREAU MINES
	Barber-Colman Proposal Range	NASA Letter 6/14/74 Mean Gas 1	Gas 2	Variable time Refuse Components RANGE	Newspaper RANGE	4" Retort 900-1700°F RANGE	18" Retort 1200-1500°F RANGE	RI 7428 RANGE
H_2	25.6-47.9	35.9	16.7	2.2-22.2	9.85-22.0	5.14-34.96	28.92-40.30	25.27-51.91
CO	13.0-26.6	19.2	17.9	15.7-45.1	26.87-42.60	23.31-35.25	16.36-27.25	12.14-25.09
CH_4	12.1-20.3	16.3	15.4	16.9-28.1	17.54-22.18	10.45-19.16	11.39-18.09	12.59-22.57
C_2H_6	0.7-1.7	1.3	1.3			.77-3.06	.20-.95	.14-2.08
C_2H_4	4.0-7.7	5.9	20.9			.45-3.05	.96-2.04	2.77-10.36
C_3H_8 C_3H_6	0-1.6	1.3	2.3					.32-2.35
CO_2	12.0-27.5	20.0	23.1	20.3-43.1	15.01-25.7	18.31-47.41	22.27-31.33	8.02-18.44
C_4H_5			0.3					0-.7
C_5 C_7			2.1					
N_2				2.0-16.1	5.4-10.55			
O_2				0-2.4	.92-2.5			
HHV	426-527	495	786	284-423	344-380			447-570

the amounts and compositions of the assorted pyrolysis products. These factors also seem to be operational in the 4" diameter retort, but to a lesser extent.

Table 1 shows a summary of some Bureau of Mines data (3). This also was obtained with an 18" diameter retort. The same general comments apply as do for the San Diego 18" retort experiments.

An examination of the data indicates that the Barber-Colman results (other than the Barber-Colman, gas 2) are not what would be expected from a pure pyrolysis process, but rather more like something from one of the 18" diameter retorts. A comparison of the mean Barber-Colman results (gas 1) was made to the closest individual results from the San Diego and Bureau of Mines experiments. This is shown in Table 2. The Barber-Colman data seems to fall between the individual San Diego and Bureau of Mines runs shown in most composition values as well as in heating value.

Therefore we would conclude that the processes occurring in the Barber-Colman tests reported must have been quite similar to those occurring in the applicable San Diego and Bureau of Mines experiments. Since we have no information on the apparatus or experimental conditions involved in the Barber-Colman tests, we cannot offer any further explanation of the results nor comment on the possible implications to scaling.

Table 2

Comparison of Other Pyrolysis Gas's to Barber Colman Pyrolysis Gas

	SAN DIEGO	BARBER-COLMAN	BUREAU MINES
H_2	34	36	31
CO	25	19	16
CH_4	13	16	23
C_2H_6	1	1	2
C_2H_4	2	6	8
C_3 & up	0	1	3
CO_2	25	20	18
HHV	365	500	560
System	Batch Retort	?	Batch Retort
Size	48"X18" dia.		26"X18" dia.
Total Pyrolysis Time	~10 hrs.		6-12 hrs.
Gas Prod. Time	~6 hrs.		
Temp Controlled	furnace		retort
Temp	900F-1500F in ~3 1/2 hr.		1380°F

The Barber-Colman gas composition identified as gas 2 does not seem to fall into the expected range for any type of refuse pyrolysis that we are aware of. The proportion of the gas in the form of CH_4 and higher hydrocarbons is unusually high and seems almost representative of something like a hydrogasification process. We would assume that some fairly carefully controlled thermochemical processing of the condensed organic constituents (tars and oils) was involved. Without more detailed information on the source of the analysis, further comment is impossible.

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2. Hoffman, D.A., "Pyrolysis of Solid Municipal Wastes," NTIS PB-222 015, July, 1973.
3. Sanner, W.S., et al., "Conversion of Municipal and Industrial Refuse into Useful Materials by Pyrolysis," Bureau of Mines RI 7428, August, 1970.

APPENDIX B1

URDC PYROLYSIS SYSTEM COMPONENT SPECIFICATIONS

PARTS LIST

URDC Pyrolysis System

Item No.	Name
201	Storage Carts (100 req'd.)
202	Cartlifter/Dumper
203	Loading Ram
204	Pyrolysis Reactor
206	Precipitator
207	Wet Scrubber
208	Back Pressure Control System
210	Gas Flow Meter
211	Excess Gas Burner
212	Excess Gas Burner Blower
213	Slag Quench Tank
214	Slag Conveyer
215	Wash Cooler
216	Wash Pump
217	Wash Level Control System
218	Oxidation Air Blower
220	Oxidation Air Heater
221	Oxidation Air Heater Burner
222	Oxidation Air Heater Burner Blower
223	Reactor Control System
224	Condensed Oil and Tar Pump
225	Oxidation Air Heater Auxiliary Burner
226	Reactor Auxiliary Burner
227	Hot Gas Blower

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

ITEM: 201

COMPONENT NAME: Storage Cart

QUANTITY REQUIRED: 100

OPERATING FLUIDS: Type 2 trash

DESCRIPTION (Functional, Concept, Materials, Etc.):

Wheeled, covered cart for remote collection, storage and handling of trash, and slag frit.

PERFORMANCE REQUIREMENTS:

Must enclose 37.5 ft^3 of municiple refuse (type 2 trash)

STRUCTURAL REQUIREMENTS:

Welded steel, hinged cover, lifting bracket(s), handle and casters, 2 fixed, 2 swivel, water tight

ELECTRICAL REQUIREMENTS:

None

INTERFACE AND ENVELOPE REQUIREMENTS:

Must interface with cart lifter and dumper. Item 202.

QUALITY AND SAFETY REQUIREMENTS:

Fireproof covered configuration.

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

ITEM: 202

COMPONENT NAME: Cart Lifter/Dumper

QUANTITY REQUIRED: 1

OPERATING FLUIDS: Use non flammable hydraulic fluid if hydraulic system is used.

DESCRIPTION (Functional, Concept, Materials, Etc.):

Hydraulic or electric lifting device with a vertical lift of approximately 22' and dumping capability at top of lift.

PERFORMANCE REQUIREMENTS:

Capacity 3000 #
Lift Ht. 22-24 ft.
Rotate and dump cart at top of lift into loading ram.

STRUCTURAL REQUIREMENTS:

Support structure

ELECTRICAL REQUIREMENTS:

3 phase 4 wire 208/220/440V 60 Hz
3 Kw max., .4 Kw avg. power

INTERFACE AND ENVELOPE REQUIREMENTS:

To interface with 201 cart and 203 loading ram

QUALITY AND SAFETY REQUIREMENTS:

Interlocks preventing lift from operating without cart in position.
TEFC motor.

ITEM: 203

COMPONENT NAME: Loading Ram

QUANTITY REQUIRED: 1

OPERATING FLUIDS: Trash, household and commerical (type 2 trash)
Non flammable hydraulic fluid used in any hydraulic systems

DESCRIPTION (Functional, Concept, Materials, Etc.):

Extrusion type trash compactor. Dumping directly into 200°F region of reactor (Item 204)

PERFORMANCE REQUIREMENTS:

100 #/hr capacity min. 40 psi compactor pressure min.
Trash bin to be covered and interface with 201 cart forming seal between cart and bin after cart dump.

STRUCTURAL REQUIREMENTS:

structural support

ELECTRICAL REQUIREMENTS:

3 phase 4 wire
208/220/440V 60 Hz
1 Kw max., .13 Kw avg. power

INTERFACE AND ENVELOPE REQUIREMENTS:

To interface with pyrolysis reactor (Item 204) and 201 cart and 202 cart lifter/dumper

QUALITY AND SAFETY REQUIREMENTS:

Fire detection and extinguishing equipment in bin
TEFC motor.

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 204

Component Name: Pyrolysis Reactor

Quantity Required: 1

Operating Fluids: Domestic refuse and sewage sludge

Description (Functional, Concept, Materials, etc.):

Vertical cylindrical reactor capable of drying, pyrolyzing, oxidizing and slaging type 2 trash and sewage sludge.

Performance Requirements:

200^{o}-2500^{o}F
Rate of reduction 972 #/hr.
40" ID 160" height inside

Structural Requirements:

Brick and refractory lines steel body lower section 80" ht. to withstand up to 2500^{o}F temp.
80" insulated steel upper section bolted to lower section.
2 piece bolted construction with air preheated jacket

Electrical Requirements:

N/A

Interface and Envelope Requirements:

6" process gas outlet
4" air inlet for oxidiation air - 1400^{o}F
4" air inlet and outlet for oxidation air from blower thru preheated jacket
6" outlet for slag, 2" inlet for sewage sludge
17.5" x 30" interface with compactor
1" inlet for water injection
1" inlet for oils and tar
Temp. ports and level sensor ports.

Quantity and Safety Requirements:

Pressure relief panel

ITEM: 206

COMPONENT NAME: Pecipitator

QUANTITY REQUIRED: 1

OPERATING FLUIDS: Raw Pyrolysis gas

DESCRIPTION (Functional, Concept, Materials, Etc.):
Electro static preceipitator for
removal of oils and tars from process gas.

PERFORMANCE REQUIREMENTS:
1650 #/hr raw gas saturated at 170°F .
Remove 42 #/hr out of 54 #/hr tars and oils in raw gas (approx. 80% removal efficiency)

STRUCTURAL REQUIREMENTS:

support structure

ELECTRICAL REQUIREMENTS:

230-460-3 phase 60 Hz or 115 VAC 60 Hz 1000 watts max. power.

INTERFACE AND ENVELOPE REQUIREMENTS:

6" dia. pipe flange inlet and outlet
Threaded 1" pipe for precipitate removal
Direct interface with item 224 pump.

QUALITY AND SAFETY REQUIREMENTS:

Pressure relief panel

ITEM: 207

COMPONENT NAME: Wet scrubber

QUANTITY REQUIRED: 1

OPERATING FLUIDS: Raw Pyrolysis Gas (output from item 206)

DESCRIPTION (Functional, Concept, Materials, Etc.): Centrifugal water spray separator to remove water vapor and some tars and oil (.68% by vol.)

PERFORMANCE REQUIREMENTS:

Gas flow rate ≈ 314.4 cfm at 170°F
Mass flow Q = 1600 #/hr gas
Temp. in 170° ave. temp out 80° ave.
Gas out 269.4 cfm at 80°
Water flow 65000 #/hr

STRUCTURAL REQUIREMENTS:

support structure

ELECTRICAL REQUIREMENTS:

N/A

INTERFACE AND ENVELOPE REQUIREMENTS:

flanged 6" gas in
flanged 6" gas out
threaded 2" water in and out

QUALITY AND SAFETY REQUIREMENTS:

Pressure relief panel

ITEM: 208

COMPONENT NAME: Back pressure control

QUANTITY REQUIRED: 1

OPERATING FLUIDS: Pyrolysis gas

DESCRIPTION (Functional, Concept, Materials, Etc.):

Electric actuator driven valve with pressure sensors and electric controller to maintain pressure downstream of reactor to a level above ambient sufficient to prevent leakage of air into combustible gas.

PERFORMANCE REQUIREMENTS:

0 - 1 psig pressure sensor
Valve pressure drop = .5" H_2O max. @ 1039 #/hr 80°F Pyrolysis gas (at .064 #/ft^3)
Pressure drop range = .5 to 20" H_2O.

STRUCTURAL REQUIREMENTS:

Line mounted valve

ELECTRICAL REQUIREMENTS:

Elec. actuator for modulating valve - remote controller.
.2 KW avg. power

INTERFACE AND ENVELOPE REQUIREMENTS:

2" dia pipe flanged inlet and outlet
Electrical connectors on valve actuator, and pressure sensors.

QUALITY AND SAFETY REQUIREMENTS:

Audiable alarm when gas pressure drops below .5" H_2O

ITEM: 210

COMPONENT NAME: Gas Flow Meter

QUANTITY REQUIRED: 1

OPERATING FLUIDS: Pyrolysis fuel gas

DESCRIPTION (Functional, Concept, Materials. Etc.):

Meter to measure and record flow rate and quantity of fuel gas delivered.

PERFORMANCE REQUIREMENTS:

Total flow readout in ft^3 . - 15×10^6 ft^3. min.
Flow rate in cfm - max 400 cfm
resetable
Flow rate 270 cfm ave. Temp. 80^oF and density .0669 #/ft^3 acfm
ΔP = .5" H_2O max.

STRUCTURAL REQUIREMENTS:

Panel mount for readout meter
line mount for indicator

ELECTRICAL REQUIREMENTS:

INTERFACE AND ENVELOPE REQUIREMENTS:

To be inserted in 2" output line from process gas blower.

QUALITY AND SAFETY REQUIREMENTS:

Weather proof construction

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ITEM: 211

COMPONENT NAME: Excess gas burner

QUANTITY REQUIRED: 1

OPERATING FLUIDS: Pyrolysis gas @ 2280 Btu/lbm lhv

DESCRIPTION (Functional, Concept, Materials, Etc.):

Gas burner to burn off excess gas not required due to lessened demand or shut off of equipment using process gas.

PERFORMANCE REQUIREMENTS:

Burn off 1600 #/hr raw process gas (saturated) Burn tube to reduce visibility and noise. Modulating valve to divert fuel gas from reactor outlet

STRUCTURAL REQUIREMENTS:

Mounting brackets

ELECTRICAL REQUIREMENTS:

Electrical actuator for modulating valve.

INTERFACE AND ENVELOPE REQUIREMENTS:

Blower air interface with 212 blower modulating valve

QUALITY AND SAFETY REQUIREMENTS:

Spark ignition and flame detector.

ITEM: 212

COMPONENT NAME: Excess Gas Burner Blower

QUANTITY REQUIRED: 1

OPERATING FLUIDS: Ambient Air

DESCRIPTION (Functional, Concept, Materials, Etc.):

Centrifugal fan to supply excess air to excess gas burner.

PERFORMANCE REQUIREMENTS:

Provide excess air to burner for combustion of fuel gas @ approx. 3000 #/hr
" 650 cfm

10" H_2O headrise

STRUCTURAL REQUIREMENTS:

support structure

ELECTRICAL REQUIREMENTS:

115/230/460 V 2.2 kw peak power

INTERFACE AND ENVELOPE REQUIREMENTS:

Interface with 211 gas burner

QUALITY AND SAFETY REQUIREMENTS:

Sound level $<$75 DB
TEFC motor

ITEM: 213

COMPONENT NAME: Slag Quench Tank

QUANTITY REQUIRED: 1

OPERATING FLUIDS: Water and Cooling Tower Water

DESCRIPTION (Functional, Concept, Materials, Etc.):

Water cooled water quench tank to turn molten slag into frit with mechanical water level control valve

PERFORMANCE REQUIREMENTS:

Quench slag from furnace
Slag flow rate 185 #/hr
Cooling water flow rate 65000 #/hr
Cooling load = 116,000 Btu/hr.
Makeup water 12 #/hr

STRUCTURAL REQUIREMENTS:

Steel wall, water tight

ELECTRICAL REQUIREMENTS:

none

INTERFACE AND ENVELOPE REQUIREMENTS:

Furnace (204)
Makeup water inlet
Cooling water inlet and outlet
Slag conveyor (214)

QUALITY AND SAFETY REQUIREMENTS:

Heat protection for operator
Water level control.

ITEM: 214

COMPONENT NAME: Slag Conveyer

QUANTITY REQUIRED: 1

OPERATING FLUIDS: Frit from slag tank

DESCRIPTION (Functional, Concept, Materials, Etc.):

Steel belt conveyor to carry frit from tank and dump into cart.

PERFORMANCE REQUIREMENTS:

185 #/hr capacity

STRUCTURAL REQUIREMENTS:

Attached to slag quench tank

ELECTRICAL REQUIREMENTS:

115/230/460 V 3/60 Hz
.5 kw power

INTERFACE AND ENVELOPE REQUIREMENTS:

Interface with quench tank (Item 213)
Discharge approx. 4 ft from floor.

QUALITY AND SAFETY REQUIREMENTS:

Covered to prevent operator injury
TEFC motor

ITEM: 215

COMPONENT NAME: Wash Cooler

QUANTITY REQUIRED: 1

OPERATING FLUIDS: Shell side (cooling water) Tube side (Condensate from process gas) H_2O 97.2% HCL .278 NH_3 .37% H_2S .13% oils and tars 2%

DESCRIPTION (Functional, Concept, Materials, Etc.):

Counter current heat exchanger to cool gas scrubber recycle water

PERFORMANCE REQUIREMENTS:

Temp. inlet shell side 60° Temp. outlet 70°
Temp. inlet tube side 80° Temp. outlet 70°
Vol. flow rate shell side 65000 #/hr
Vol. flow rate tube side 65000 #/hr
Pressure tube side 40 psi
Pressure drop each side = 2 psi.

STRUCTURAL REQUIREMENTS:

Removable heads for cleaning of tube side

ELECTRICAL REQUIREMENTS:

none

INTERFACE AND ENVELOPE REQUIREMENTS:

2" pipe connections

QUALITY AND SAFETY REQUIREMENTS:

ITEM: 216

COMPONENT NAME: Wash Pump

QUANTITY REQUIRED: 1

OPERATING FLUIDS: Condensate from fuel gas scrubber
H_2O 97.2%; HCL .27%; NH_3 .37%; H_2S .13%; tars and oil 2%

DESCRIPTION (Functional, Concept, Materials, Etc.):

Centrifugal pump to recirculate water from scrubber thru 215 wash cooler back to scrubber.

PERFORMANCE REQUIREMENTS:

Flow rate 130 GPM
Pressure Rise
Inlet temp. 70°
Head approx. 40 psi

STRUCTURAL REQUIREMENTS:

Mounting bracket or base

ELECTRICAL REQUIREMENTS:

110 V or 208 V
1.36 kw avg. power

INTERFACE AND ENVELOPE REQUIREMENTS:

2" inlet 2" NPT outlet

QUALITY AND SAFETY REQUIREMENTS:

TEFC motor

ITEM: 217

COMPONENT NAME: Wash Level Control System

QUANTITY REQUIRED: 1

OPERATING FLUIDS: Condensate from gas scrubber

DESCRIPTION (Functional, Concept, Materials, Etc.):

To control level of liquid high and low in scrubber valve and controller dumping excess water to waste sewage system.

PERFORMANCE REQUIREMENTS:

Motor operated valve
Pass 500 #/hr at 5 psi pressure drop max.
Max pressure = 10 psi

STRUCTURAL REQUIREMENTS:

ELECTRICAL REQUIREMENTS:

110 V or 208 V .1 kw avg. power

INTERFACE AND ENVELOPE REQUIREMENTS:

Mount to gas scrubber for level sensing

QUALITY AND SAFETY REQUIREMENTS:

Weather proof components

ITEM: 218

COMPONENT NAME: Oxidation air blower

QUANTITY REQUIRED: 1

OPERATING FLUIDS: Ambient air

DESCRIPTION (Functional, Concept, Materials, Etc.):

Centrifugal blower supplying oxidation air for pyrolysis reactor

PERFORMANCE REQUIREMENTS:

167.5 cfm flow rate
40" H_2O pressure rise
Ambient Temp. inlet

STRUCTURAL REQUIREMENTS:

Mounting base

ELECTRICAL REQUIREMENTS:

115/230/460 V 3/60 Hz
2 KW avg. power

INTERFACE AND ENVELOPE REQUIREMENTS:

2 " flange mounting output
4" flange inlet

QUALITY AND SAFETY REQUIREMENTS:

Sound level $<$75 DB
TEFC motor

ITEM: 220

COMPONENT NAME: Oxidation air heater

QUANTITY REQUIRED: 1

OPERATING FLUIDS: Hot Side heated air and combustion products from air heater burner
Cool side air from air blower

DESCRIPTION (Functional, Concept, Materials, Etc.): Gas to gas heat exchanger

To take superheated gas from Item 218 @ 2500°F and preheat combustion air to 1400°F

PERFORMANCE REQUIREMENTS:

Cool side air inlet temp. = 80°F
Cool side air outlet temp. 1400°F
Hot side air inlet temp. 1800°F
hot side air outlet temp. 500°F
Vol. of air heated 173.9 cfm on (292 #/hr)
Vol. of combustion products = 436 #/hr.

Pressure drop 5" H_2O hot side
15" H_2O cold side

STRUCTURAL REQUIREMENTS:

Insulated floor mounting structure

ELECTRICAL REQUIREMENTS:

None

INTERFACE AND ENVELOPE REQUIREMENTS:

2" flange for combustion air in
4" flange for combustion air out
4" flange for heated air in
4" flange for heated air out

QUALITY AND SAFETY REQUIREMENTS:

Fully insulated

ITEM: 221

COMPONENT NAME: Oxidation Air Heater Burner

QUANTITY REQUIRED: 1

OPERATING FLUIDS: Ambient air, process gas

DESCRIPTION (Functional, Concept, Materials, Etc.):

Process gas burner to produce hot gas used to preheat reaction air

PERFORMANCE REQUIREMENTS:

Process gas heating valve 2280 Btu/lb
Burner output - 320,000 But/hr
Air supply flow rate - 64 cfm
Air pressure - .5 psig
Process gas pressure .5 psig

STRUCTURAL REQUIREMENTS:

Flange mount to 220 oxidation air heater

ELECTRICAL REQUIREMENTS:

110/208 V spark ignition

INTERFACE AND ENVELOPE REQUIREMENTS:

Gas inlet
Air inlet

QUALITY AND SAFETY REQUIREMENTS:

Spark ignition and flame detector.

ITEM: 222

COMPONENT NAME: Oxidation Air Heater Burner Blower

QUANTITY REQUIRED: 1

OPERATING FLUIDS: Ambient Air

DESCRIPTION (Functional, Concept, Materials, Etc.):

Centrifugal blower to
Provide air for oxidation air heater burner

PERFORMANCE REQUIREMENTS:

Air inlet temp. - ambient
Flow rate - 95 cfm
Pressure rise - 10" H_2O

STRUCTURAL REQUIREMENTS:

Mounting bracket or plate

ELECTRICAL REQUIREMENTS:

115/230/460 V 3/60 Hz
.32 kw avg. power

INTERFACE AND ENVELOPE REQUIREMENTS:

2" flange outlet

QUALITY AND SAFETY REQUIREMENTS:

Sound level < 75 DB
TEFC motor

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

ITEM: 223

COMPONENT NAME: Reactor Control System

QUANTITY REQUIRED: 1

OPERATING FLUIDS: None

DESCRIPTION (Functional, Concept, Materials, Etc.):

Floor mounted console (sheet metal) containing electronic circuitry and system display instruments

PERFORMANCE REQUIREMENTS:

Temp. sensor readouts
Press. sensor readouts
Operational lights
Emergency lights and buzzers
Air blower speed control
Burner controls
Trash level/feed control
On off switches for item operation

STRUCTURAL REQUIREMENTS:

Floor mounting

ELECTRICAL REQUIREMENTS:

110/208 V ; 5 kw avg. power

INTERFACE AND ENVELOPE REQUIREMENTS:

Electrically interface with remote sensors

QUALITY AND SAFETY REQUIREMENTS:

Safety interlocks on doors exposing circuitry - NEMA 12 standard cabenetry weather proof electrical components.

ITEM: 224

COMPONENT NAME: Oil and Tar Pump

QUANTITY REQUIRED: 1

OPERATING FLUIDS: Condensed oils and tars and H_2O from precipator

DESCRIPTION (Functional, Concept, Materials, Etc.): posative displacement pump to pump tars and oils from precipator back to pyrolysis reactor

PERFORMANCE REQUIREMENTS:

Flow rate 42 #/hr
Pressure rise - 1 psi
Inlet temp. - 170^{o}F
Fluid viscosity = 300 SSU
Fluid density = 60 #/ft^3

STRUCTURAL REQUIREMENTS:

ELECTRICAL REQUIREMENTS:

110/208 V .33 kw peak .033 kw avg. power

INTERFACE AND ENVELOPE REQUIREMENTS:

3/4" NPT inlet and outlet
mounted on precipitator item 206.

QUALITY AND SAFETY REQUIREMENTS:

TEFC motor

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 225

Component Name: Oxidation Air Heater Auxiliary Burner

Quantity Required: 1

Operating Fluids: Air, Auxiliary Fuel (Fuel Oil)

Description (Functional, Concept, Materials, etc.):

Oil fired burner with blower to provide startup heat for oxidation air heater

Performance Requirements:

Burner output 320,000 Btu/hr
Combustion products outlet temp. 1800°F
Burner outlet pressure 5" H_2O above ambient

Structural Requirements:

Flange mounted

Electrical Requirements:

110/208 V
spark ignition

Interface and Envelope Requirements:

Interface with reaction air heater

Quantity and Safety Requirements:

TEFC motor
Flame indication
Sound level $<$75 Db

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 226

Component Name: Reactor Auxiliary Burner

Quantity Required: 1

Operating Fluids: Air, Auxiliary Fuel (Fuel Oil)

Description (Functional, Concept, Materials, etc.):

Oil fired burner with blower to provide sufficient heat to start up and maintain pyrolysis reaction in furnace.

Performance Requirements:

Burner Output 320,000 Btu/hr.
Combustion products outlet temp. = 2500°F min
Burner Outlet pressure = 10" H_2O above ambient
Non operating burner outlet temp. = 2500°F
Non operating burner outlet pressure = 10" H_2O above ambient

Structural Requirements:

Flange mounted

Electrical Requirements:

110/208 V
spark ignition

Interface and Envelope Requirements:

Interface with pyrolysis reactor
Interface with auxiliary fuel supply

Quantity and Safety Requirements:

TEFC motor
Flame indication
Sound level $<$75 Db

ITEM: 227

COMPONENT NAME: Hot Gas Blower

QUANTITY REQUIRED: 1

OPERATING FLUIDS: Raw Pyrolysis Gas

DESCRIPTION (Functional, Concept, Materials, Etc.):

Centrifugal fan with stainless steel shaft and rotor

PERFORMANCE REQUIREMENTS:

Flow 1597 #/hr (.067 #/ft^3 @ 60^o)
Temp. 170^oF normal, 500^oF max.
Pressure Rise = 10" H_2O

STRUCTURAL REQUIREMENTS:

Mounting Plate

ELECTRICAL REQUIREMENTS:

115/230/460 V 3/60 Hz
1.33 kw avg. power

INTERFACE AND ENVELOPE REQUIREMENTS:

6" pipe flange, inlet and outlet

QUALITY AND SAFETY REQUIREMENTS:

Sound level $<$75 DB
TEFC motor

APPENDIX B2

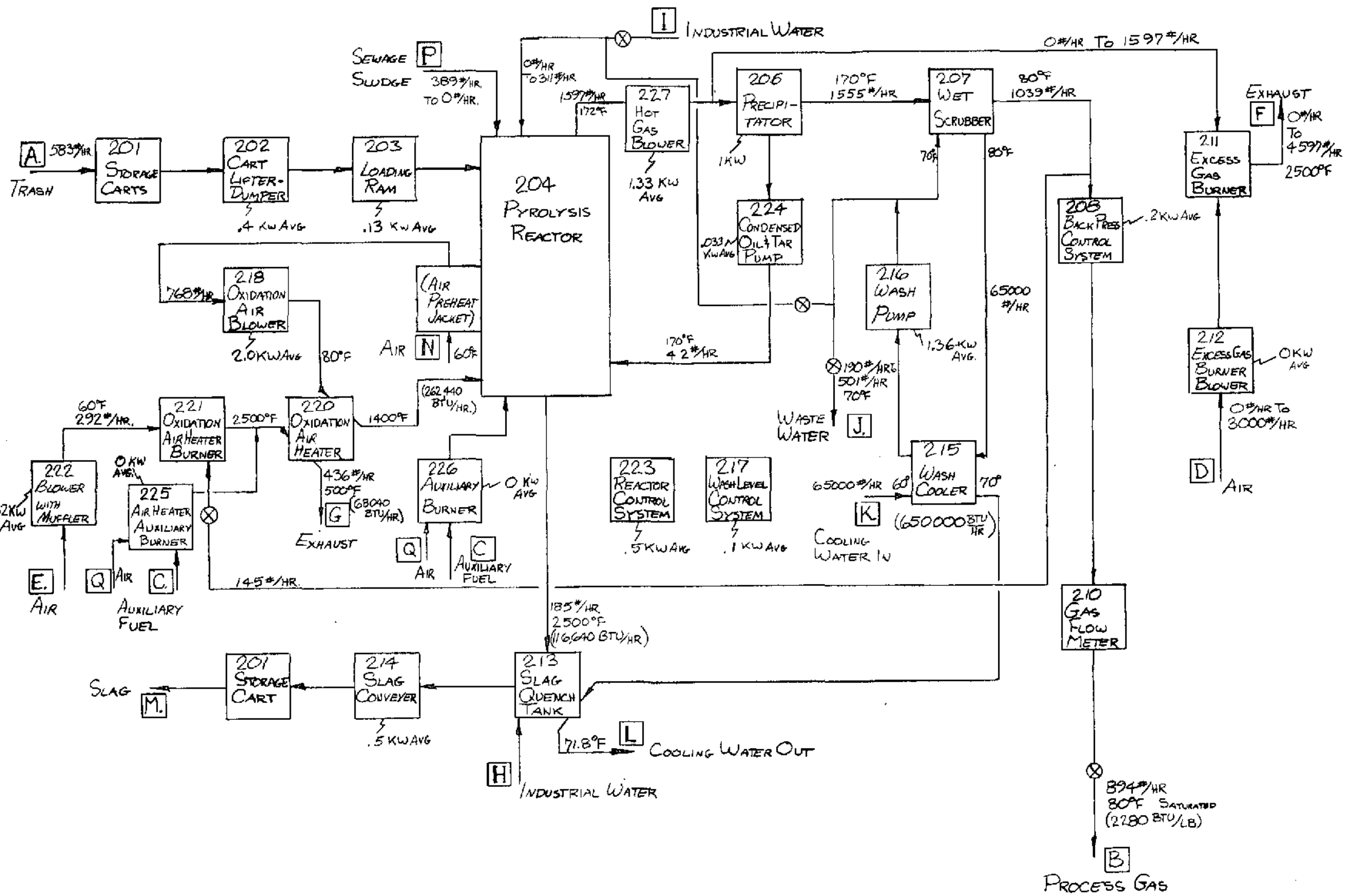
URDC PYROLYSIS SYSTEM DRAWINGS AND SKETCHES

URDC PYROLYSIS SYSTEM DRAWINGS AND SKETCHES

In this appendix drawings and sketches of the URDC Pyrolysis System are presented. It should be noted that these conceptual drawings represent some configuration modifications to actual hardware produced by URDC in the past. These changes were conceived to adapt URDC experience to the IUS interface requirements and to reflect current thinking at Hamilton Standard as to the appropriate configuration which would incorporate desirable state-of-the-art design features for a vertical shaft reactor. Therefore, the drawings should be considered as the composite thinking of Hamilton Standard and its subcontractors as to the current state-of-the-art for the basic concept of a vertical shaft reactor.

Drawings presented are:

Hamilton Standard
DIVISION OF UNITED AIRCRAFT CORPORATION



URDC Pyrolysis System Block Diagram

FIGURE 1

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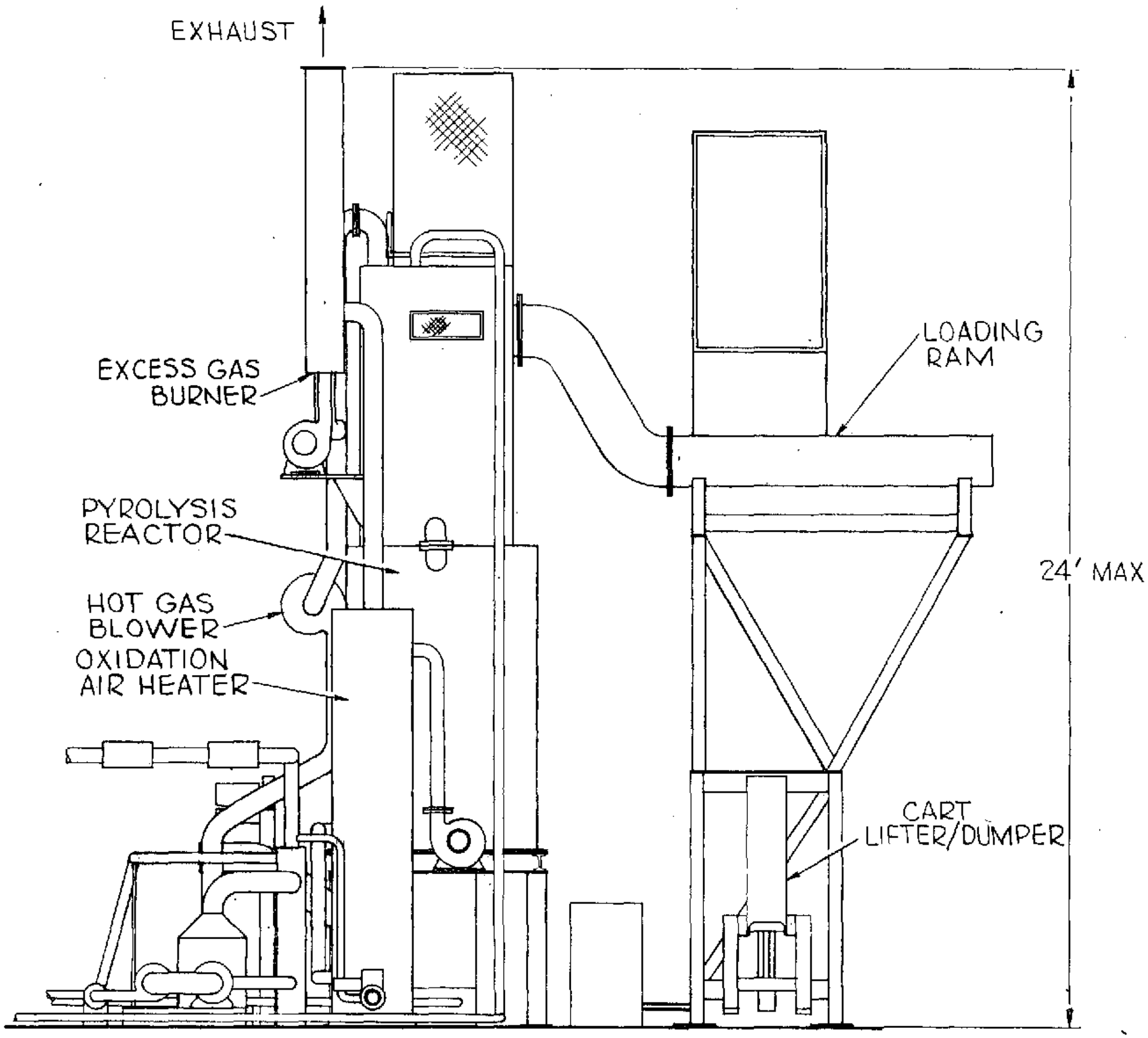
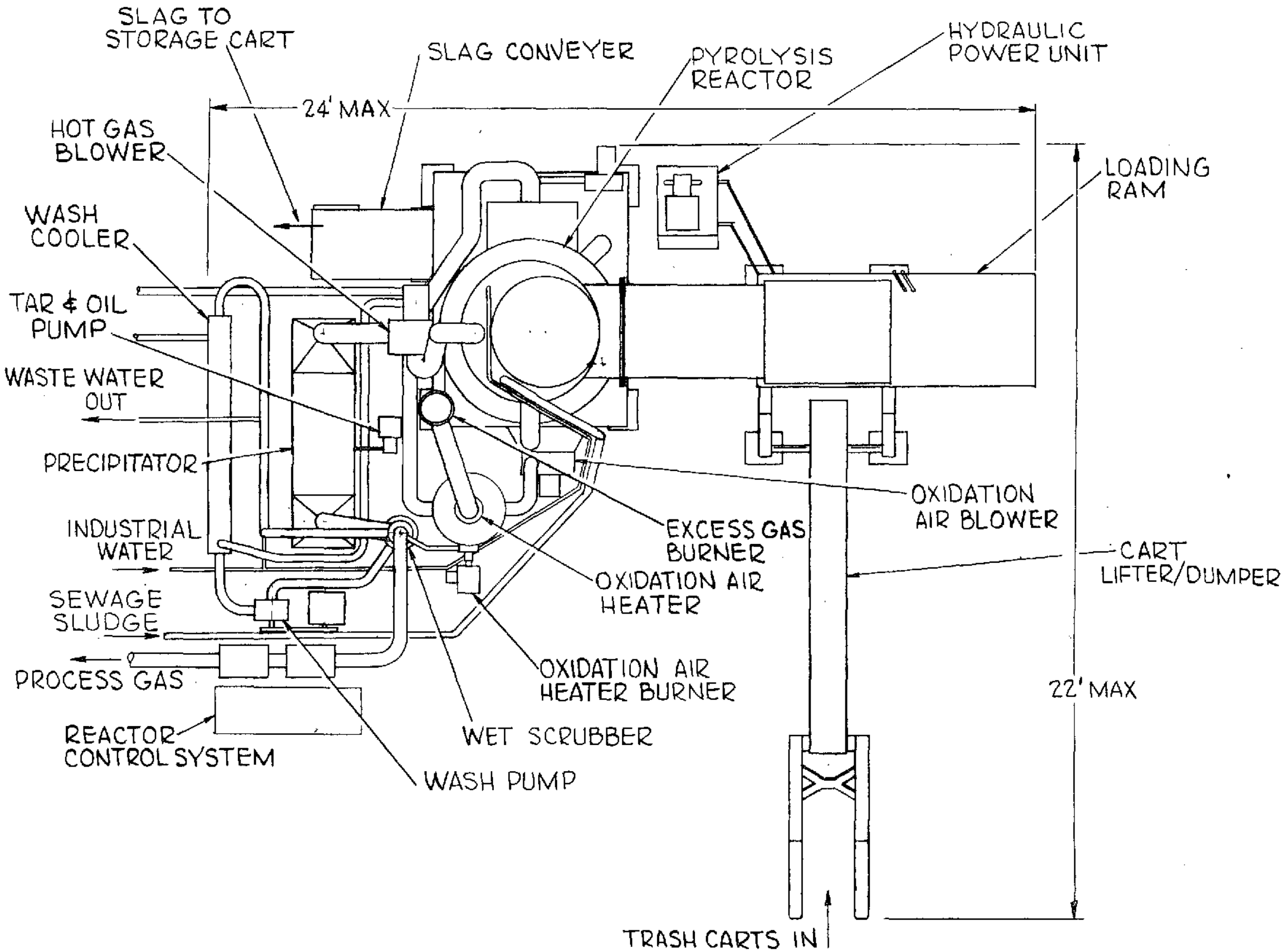


URDC Pyrolysis System Elevation

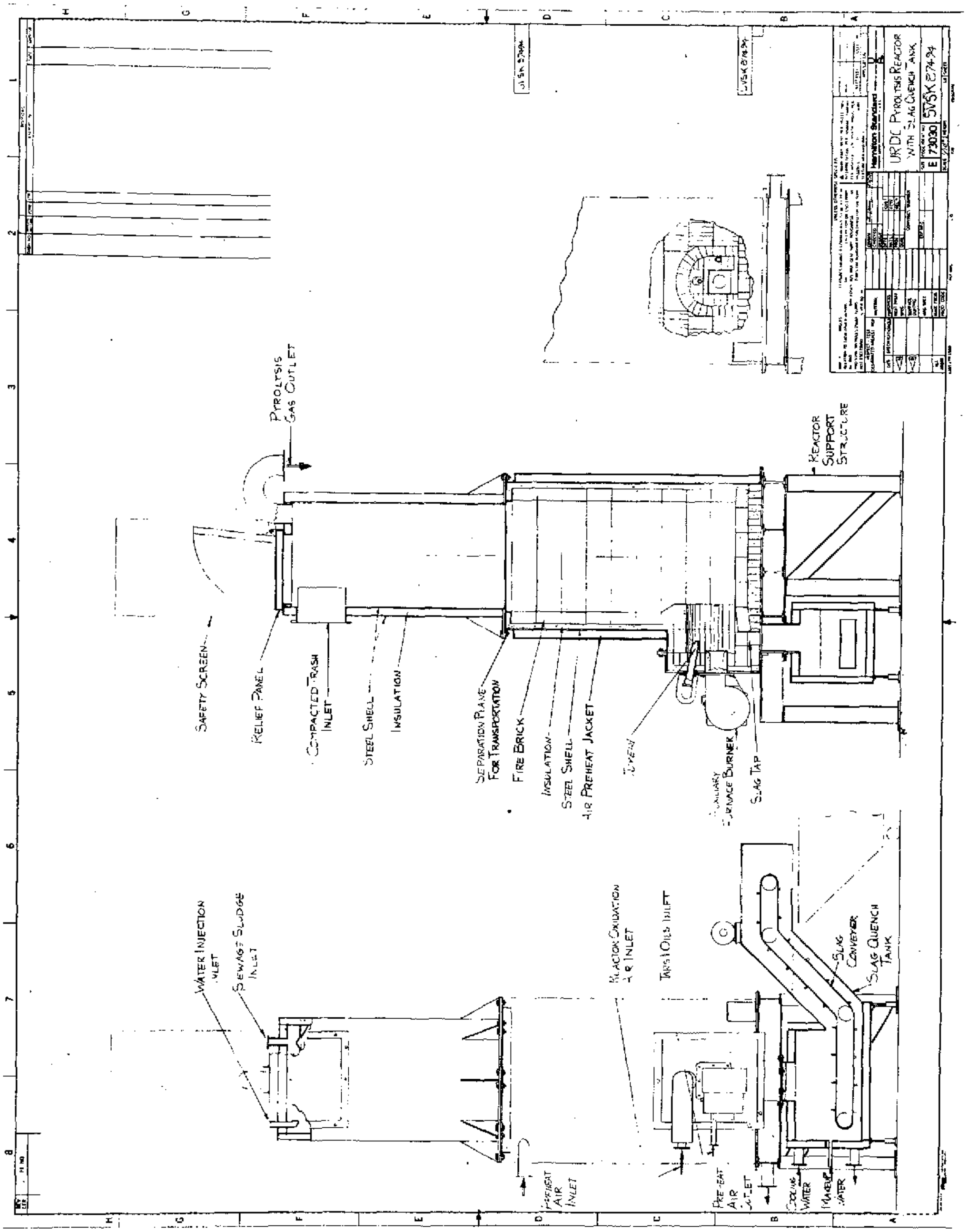
FIGURE 2



URDC Pyrolysis System Plan View

FIGURE 3

Hamilton Standard
DIVISION OF UNITED AIRCRAFT CORPORATION



URDC PYROLYSIS REACTOR WITH SLAG QUENCH TANK

FIGURE 4

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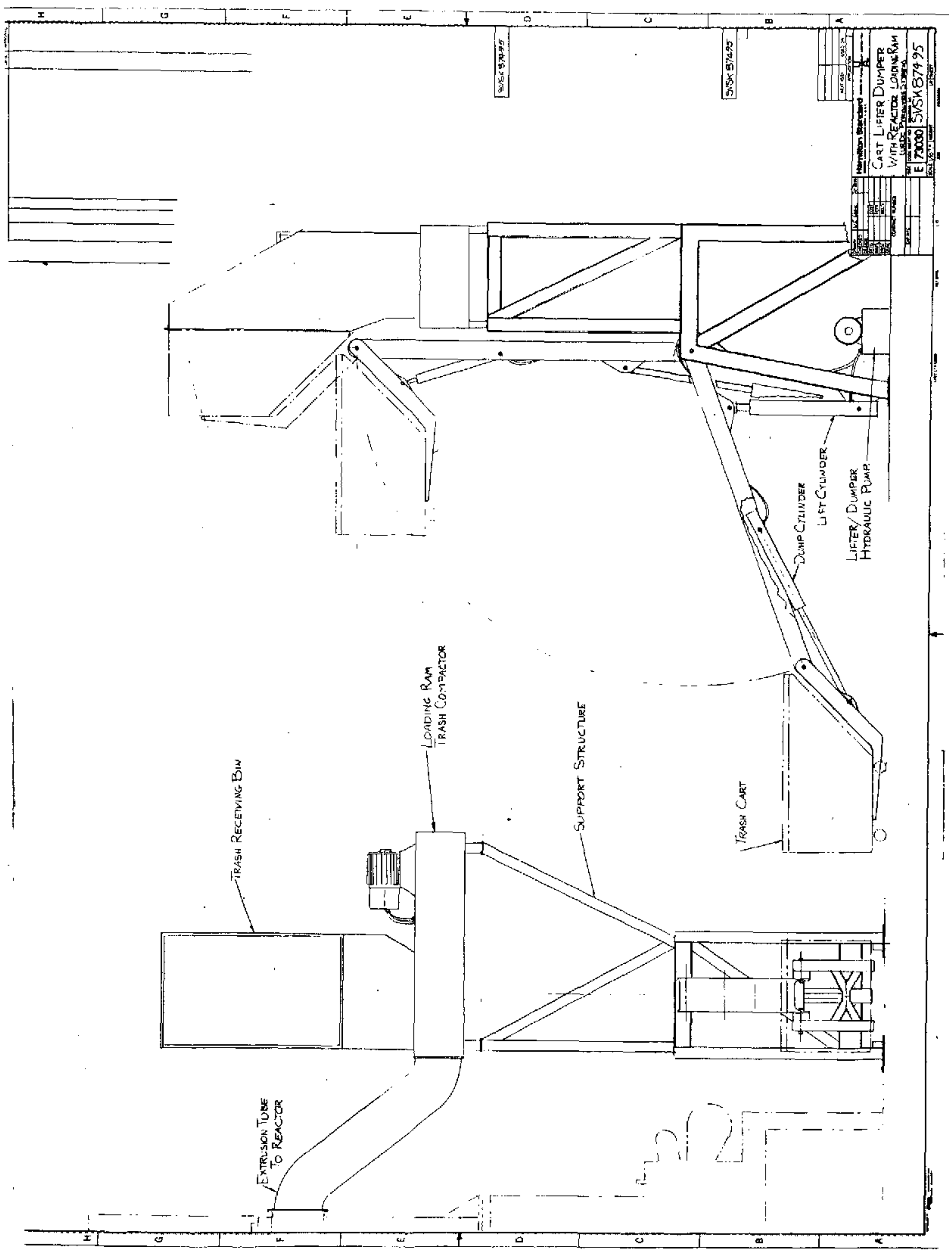

CART LIFTER (DUMPER WITH REACTOR LOADING RAM
(URDC PYROLYSIS SYSTEM)

FIGURE 5

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APPENDIX B3

PERFORMANCE CALCULATIONS FOR THE URDC PYROLYSIS SYSTEM

PERFORMANCE CALCULATIONS FOR THE URDC PYROLYSIS SYSTEM

Introduction

The calculation of complete internally consistent heat and mass balances for a fixed bed gasifier is relatively straightforward and reliable since the system is in a thermodynamic sense quite simple. Reliable experimental data is required and is available, although the precision and applicability of certain data to a specific situation could be questioned.

From an analysis standpoint, the main advantage of the fixed bed process over an externally heated furnace approach, such as the Barber-Colman system is that there is no need to make an estimate or measurement of the pyrolysis process heat of reaction. In essence, this measurement is replaced by the measurement of the gasification air quantity requirement. This fact makes calculations for the fixed bed process simplier since the gasification air can be measured and relate to operating conditions. The effective heat of reaction is difficult to measure and even more difficult to estimate. The reason for this is that the furnace situation is not a pure pyrolysis process (i.e., simple decomposition of a solid through heating with no further reaction). Even though air is excluded, there is opportunity for significant gas/gas and gas/solid reactions. The fact that they do occur is demonstrated by the very considerable differences in pyrolysis performance obtained by investigators such as

Kaiser, Hoffman, and the Bureau of Mines for essentially similar configurations. Since the performance variations are quite large and are dependent on both geometry, scale, and operating conditions, in some fashion most difficult to predict, performance projections are subject to a very high level of uncertainty

The basic corresponding parameter for the fixed bed gasifier - gasification air/refuse - is quite well established and relatively insensitive to variations in feed or process conditions. For example, the oxygen consumption in an air gasifier or oxygen gasifier are essentially the same. Even if the feed is changed to coal, basic performance is similar as evidenced by the remarkably similar nitrogen concentrations in the fuel gases from gas procedures and similar air blown coal gasifiers and air gasifiers feeding ordinary municipal wastes.

Since the fixed bed gasifier is relatively simple, it is possible to calculate the product gas composition with only a few assumptions necessary on the relations between key constituents. For example, it is possible to set up a complete closed and internally consistent detailed mass and energy balance. Although the resulting composition is not highly accurate, it is still quite useful. It provides a test of the reasonableness of calculations made and also provides the basis for a most powerful tool for the prediction of the effect of changing conditions on system performance. As yet, some of the basic parameters are

not known with the level of precision that would be desired, but the basic knowledge is there. Certainly more data would be highly desirable in some areas. For example, the quantities of tars and oils produced are not known as reliably as they should be; it certainly would be desirable to have a completely closed, single point, experimentally determined heat and mass balance for use as a test of any detailed model developed.

Performance

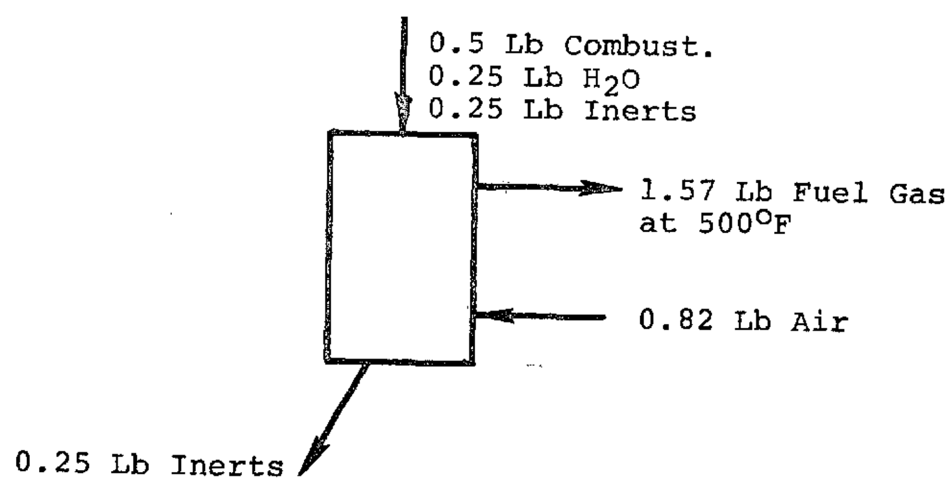
The high water levels in the waste feed to the IUS pyrolysis system result in operating conditions significantly different than those usually encountered. Thus, scaling is required to predict performance. Fortunately, the fixed bed system is simple enough and well enough understood to allow scaling on a quite rational basis. This was accomplished as follows for an input of one pound waste.

The best value obtainable for the amount of condensable organics (tars and oils) which would be produced under typical fixed bed gasification conditions, feeding typical refuse, is 0.08 pound tars and oils per pound of refuse (unpublished Union Carbide data). This was assumed to be proportional to the combustibles in the feedstock. For 0.5 pound combustibles in ordinary refuse, and 0.34 pound combustibles in IUS waste, the resulting production of tars and oils for the IUS situation is 0.054 pound. It was further assumed that 80% (0.043 pound) would be recovered in the electrostatic precipitator and recycled to the gasifier,

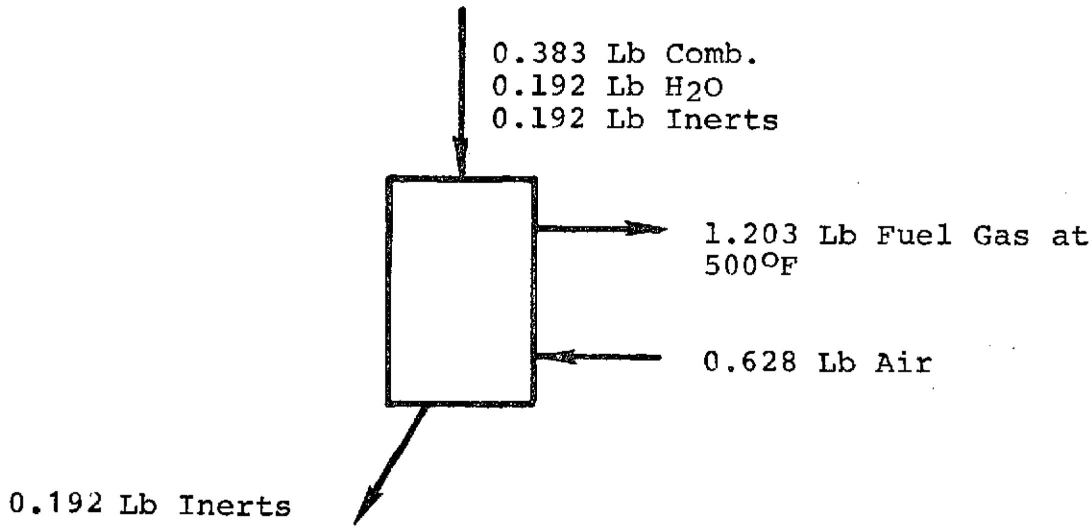
while the remaining 20% (0.011 pound) would be lost with the scrubber effluent.

The general behavior of the recycled tars and oils was assumed to be similar to that of the combustible portion of the waste feed. Thus, the effective combustible input to the gasifier was assumed to be the 0.34 pounds in the waste feed, plus the recycled tars and oils, for a total of 0.383 pound.

The gasification air requirement, which is the key variable in the performance calculation, could then be chosen as follows. The starting point was assumed to be a system feeding typical refuse. The values chosen are consistent with both URDC and Union Carbide experimental results.



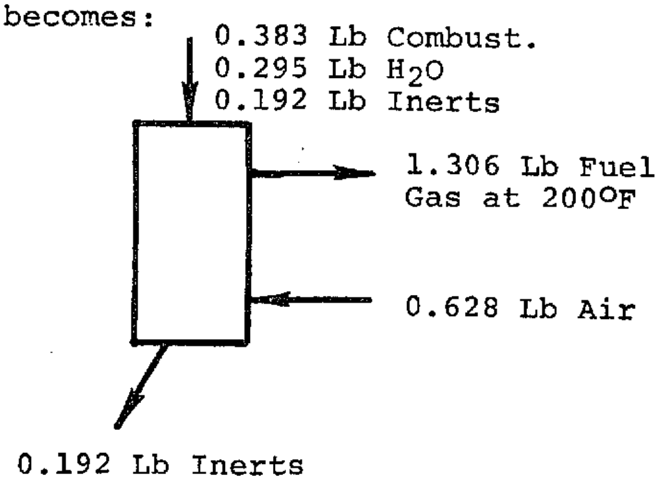
These values can be ratioed so that the combustible feed will match the effective combustibles for the IUS waste. Results are:



Enough additional water can be introduced with the waste to lower the fuel gas temperature to saturation without any effect on the process beyond lowering the fuel gas temperature to approximately 200°F. Equating the sensible heat requirement of the fuel gas to the heat required to vaporize and heat to 200°F additional water in the feed allows the calculation of that additional water:

$$\text{Delta } H_2O = (1.203)\ (0.32)\ (500-200)/(1118) = 0.103 \text{ Lb}$$

The equivalent mass balance becomes:



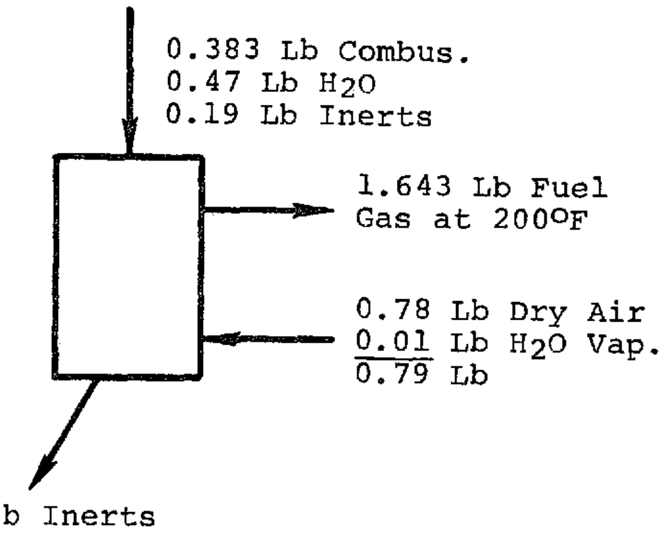
This is still not sufficient to vaporize all of the water in the IUS waste feed. The heat required to vaporize the additional water can be calculated as follows:

$$Q = (0.47-0.295)\ (1118) = 196\ \text{Btu}$$

The source of the required additional heat must be combustion of added gasification air with char or other pyrolysis products. The heat released per pound of air varies depending on whether oxidation goes to CO or all the way to CO_2. Since increasing the oxidizer flow tends to shift the system towards CO_2, the higher valves are more likely. However, to be conservative, an average of the available heat for oxidation to CO and to CO_2 was taken. The available heat is the heat of combustion of char (to the particular product assumed), plus the sensible heat in the gasification air (introduced at 1,400°F), less the sensible heat in the combustion products (removed at 200°F). The resulting value is 1,300 Btu/lb air. The additional air requirement then can be calculated as follows:

$$\text{Delta Air} = (196\ \text{Btu})/(1300\ \text{Btu/Lb Air}) = 0.151\ \text{Lb}$$

This gives a total gasification air input of 0.779 pound. Assuming normal humidity (0.013 lb H_2O/lb dry air), and rounding slightly, the gross mass balance becomes:



At this point, the gross mass inputs and outputs have been defined except for the water output. This was estimated by assuming that half of the oxygen in the waste feed shows up as water in the fuel gas. This value is consistent with Union Carbide data for fixed bed gasification and is in the same magnitude as for most pyrolysis experiments. This gives a total of 0.543 pound water in the fuel gas, 0.47 pound from the original waste, and 0.073 pound from pyrolysis.

The inorganic constituents of the fuel gas were estimated as follows. Half of the nitrogen in the waste was assumed to show up in the fuel gas as NH_3, the rest as N_2. All of the sulfur and chlorine in the waste was assumed to be present in the fuel gas as H_2S and HCl. This is conservative, at least for the waste feed composition assumed, since there would be at least some tie-up of these in the slag.

The fuel gas was assumed to consist of CO, CO_2, H_2, N_2, O_2, CH_4, C_2H_4, and C_2H_2. Equal quantities of C_2H_4 and C_2H_2 were assumed. CH_4 was taken as three times C_2H_4. The tars and oils were represented by $CH_{0.8}O_{0.1}$. The elemental composition given in the IUS Waste Feed Data (Appendix D1) were used to characterize the input waste.

All energy calculations used 60°F as the base state. The values were rounded to the nearest 10 Btu. The waste input HHV of 3,400 Btu/lb derived in Appendix D1 was corrected to LHV using 1,060 Btu/lb water in combustion products. The result is 2,680 Btu. An LHV of 14,000 Btu/lb was used for tars and oils (vapor state). This is consistent with the rather limited experimental data available and with the composition as assumed ($CH_{0.8}O_{0.1}$). The sensible heat input with gasification air was calculated for an input temperature of 1,400°F. Heat loss associated with the slag was calculated for a specific heat of 0.27 and a 2,400°F exit temperature. To be conservative, the heat loss per pound from the gasifier calculated for the original URDC system proposal (Appendix A1) was used even though the IUS system is larger and, therefore, would have a somewhat lower heat loss per pound. The values from Appendix A1 are a heat loss of 60,000 Btu/hr for a 500 lb/hr system, resulting in a heat loss of 120 Btu/lb. However, a transposition error was made, and a heat loss of 140 Btu/hr was used in all of the calculations. Since this was not

discovered until after calculations were complete, and since it is in the direction of added conservatism (17% additional heat loss), it was not changed.

With the assumptions described, the only unknown as far as the gasifier mass and heat balances are concerned is the composition of the fuel gas. Of the eight fuel gas constituents, the known nitrogen content and the two relations between hydrocarbons assumed, reduces the number of unknowns to five. There are three elemental mass balance equations that must be satisfied (C, H, O). Furthermore, the composition must be such that an energy balance around the gasifier is satisfed. This gives a fourth equation. Thus, a solution requires only one further assumption. This cannot be a rigid assumption since a bad one will result in impossible composition. In effect, the assumption is a matter of picking a value for one parameter (O_2 was used), calculating the resulting fuel gas composition and then adjusting the chosen value to give an overall composition with no negative values and reasonable agreement with known experimental results. The resulting fuel gas composition and some of its basic thermodynamic properties are given in Table 1.

The gas cleanup train could then be defined. The precipitator was assumed to operate at approximately 200°F and remove 80% of the tars and oils. This is consistent with Union Carbide experience. The remaining condensable organics, as well as the

TABLE 1
URDC FUEL GAS

Composition (Mol %):

H_2	15.3%
CO	28.1%
CH_4	1.0%
C_2H_4	0.3%
C_2H_2	0.3%
CO_2	3.3%
O_2	1.4%
N_2	50.3%
	100.0%

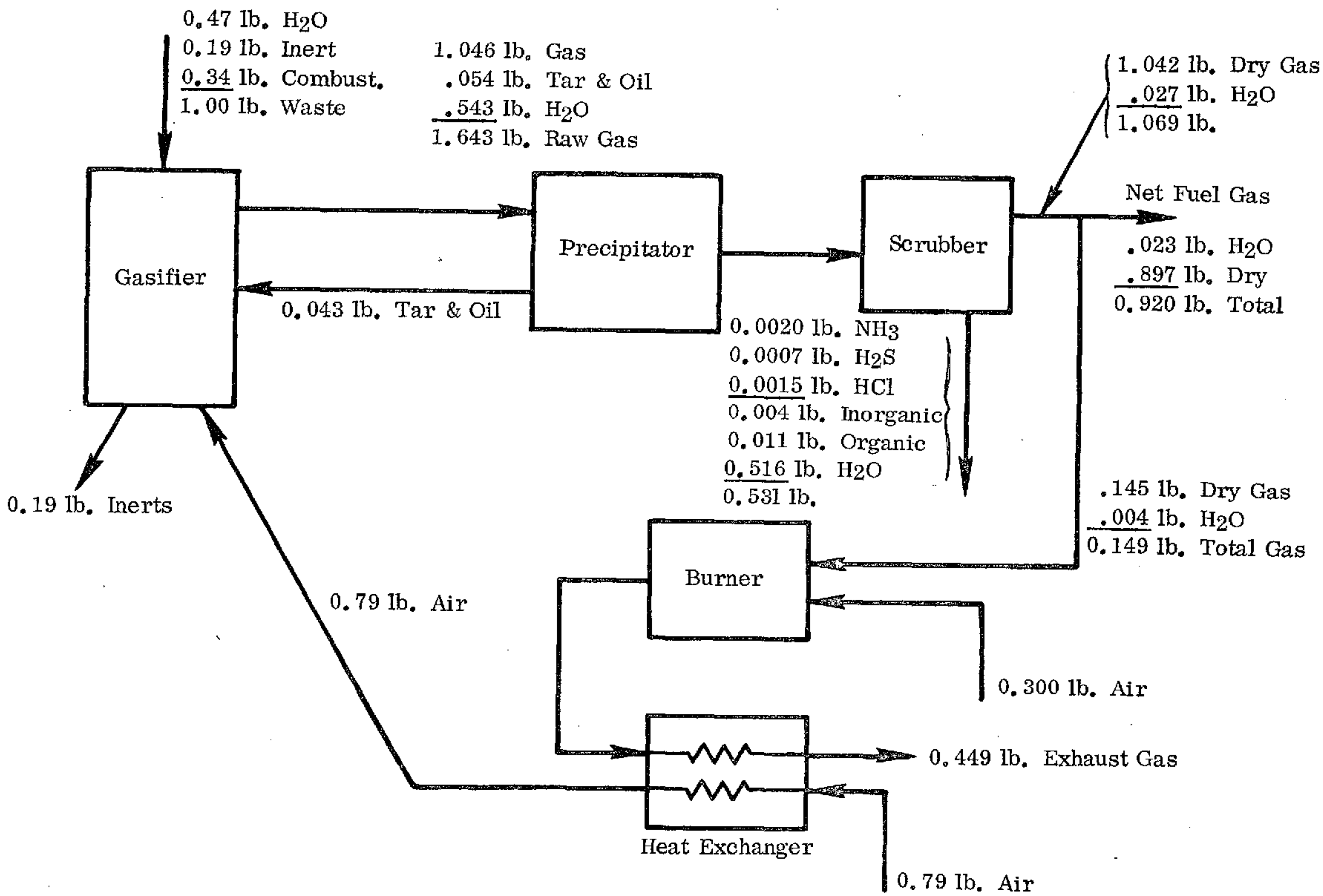
Properties:

Molecular Weight:	24.5 Lb/Mol
HHV:	159 Btu/Ft^3 Gas
LHV:	150 Btu/Ft^3 Gas
	70 Btu/Ft^3 Stoich. Mix.
	78 Btu/Ft^3 Stoich. Comb. Prod.
Stoichiometric Volume:	1.14 Ft^3 Air/Ft^3 Gas
	2.14 Ft^3 Mix./Ft^3 Gas
	1.92 Ft^3 Comb. Prod./Ft^3 Gas

inorganics, were assumed to be removed in the wet scrubbers. The bulk of the water and the fuel gas also would be condensed and removed with the scrubber effluent (the fuel gas leaving the scrubber was assumed saturated at 80°F). The scrubber would have to remove enough heat to cool the raw gas from 200°F as well as condense the water.

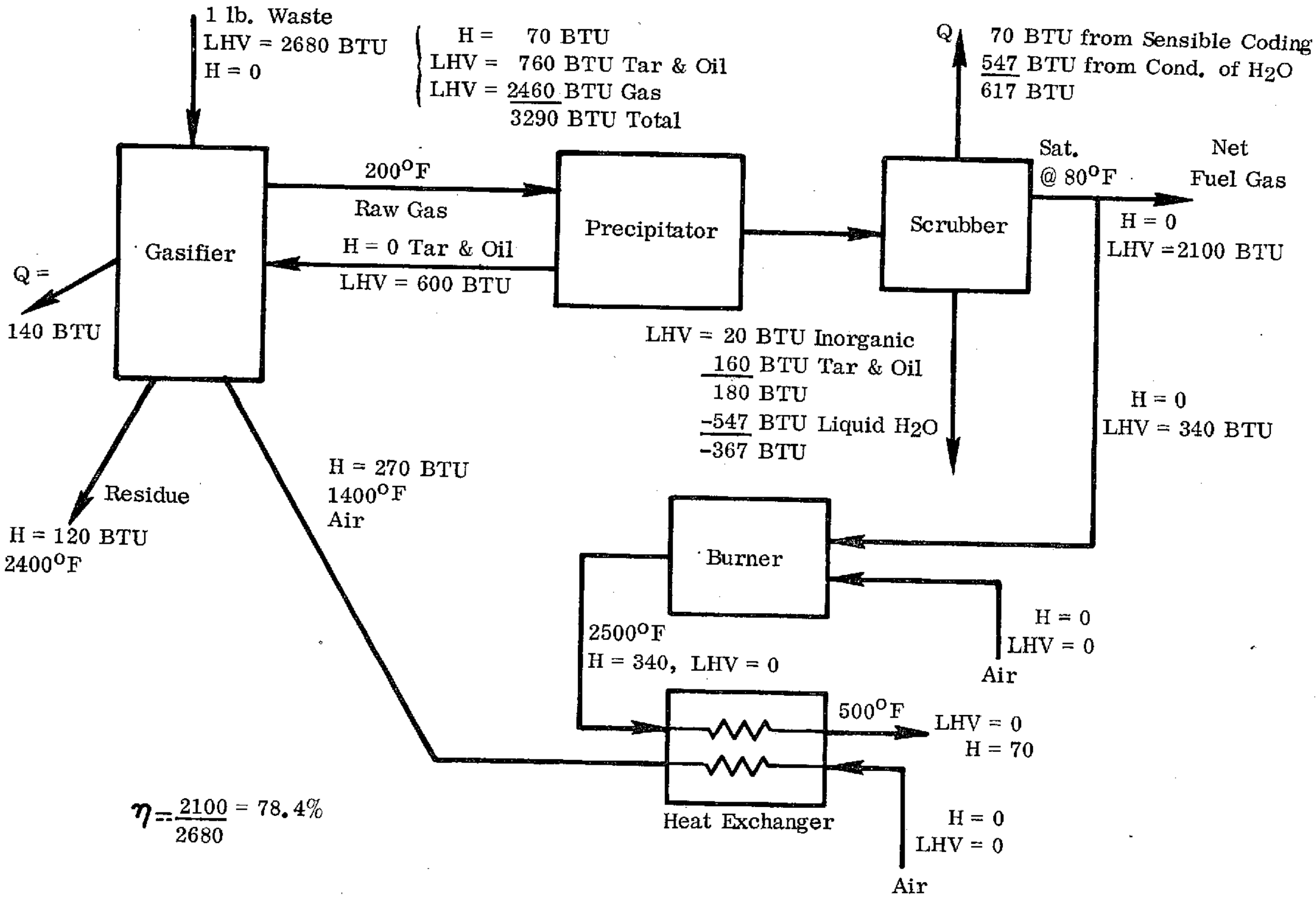
The performance of the burner/heat exchanger used to heat gasification air was calculated using data from Trinks for producer gas. Since the producer gas data given is for a heating value of 129 Btu/ft^3, the results are slightly conservative. Heat exchanger inlet temperatures were limited to 2,500°F to simplify heat exchanger design and maximize its reliability. This would require approximately 50% excess air. The exhaust temperature from the heat exchanger was taken as 500°F which would give a 19% loss. This was rounded up to give a 20% loss or 80% efficiency. The required heat exchanger effectiveness was checked (83% at a heat capacity ratio of 0.65) and found to be reasonable for a multi pass cross flow heat exchanger.

Once the efficiency of the gasification air heater was defined, the system energy and mass balances could be closed. The final results are shown on Figures 1 and 2.



URDC SYSTEM MASS BALANCE

FIGURE 1



URDC System Energy Balance (Electrical Not Included)

FIGURE 2

APPENDIX B4

URDC PYROLYSIS SYSTEM COSTS

B4

URDC PYROLYSIS SYSTEM COSTS

An economic analysis of the URDC pyrolysis system was made at 6, 45 and 250 ton/day sizes based on municipal refuse disposal or utility operation on continuous duty (24 hrs/day) for six days per week. Capital outlay for an installed system, annual operation and maintenance, and the dollar value of the net fuel gas produced are shown in Table 1. These estimates are also illustrated in Figures 1 through 3 compared with the Barber-Colman system. Detail rationale for these estimates is presented in the following sections.

CAPITAL COSTS

The estimates of capital outlay for the 6, 45 and 250 TPD installed systems were based on estimates of component costs for each system increased by 36 percent (determined from estimates on the 6 TPD system) for installation, duct, pipe, wire and site preparation and 50 percent for engineering and supplier handling. Table 2 summarizes these results.

Component cost estimates for the three system sizes are shown in Table 3. Table 4 shows the estimates for duct, pipe, wire, and installation for the six TPD system.

The component costs shown in Table 3 represent a mixture of firm letter quotes from suppliers, telephone quotes, catalog prices, and estimates based on comparisons with known prices. All values represent the FOB cost at point of manufacture.

TABLE 1
URDC UTILITY PYROLYSIS SYSTEM ECONOMIC EVALUATION

(Thousands of Dollars)

TPD	Capital Outlay	Annual O&M (1)	Annual Net Value Fuel Produced (2,3)
6	$ 132.2	$127.4	$ 27.2
45	$ 398.8	$143.1	$ 205.4
250	$1,838.1	$207.0	$1,141.7

NOTES:

(1) Does not include electrical power costs.

(2) Estimated at $1.85/10^6$ Btu (LHV).

(3) Electrical power deducted from gross fuel at 35.1% electrical conversion efficiency based on LHV.

TABLE 2
URDC PYROLYSIS SYSTEM CAPITAL COSTS

	($1,000)		
TPD	6	45	250
Component Costs	71.1	214.4	988.2
Duct, Pipe, Wire, Etc. (36%)	25.6	77.2	355.8
Engineering and Supplier Handling (50%)	35.5	107.2	494.1
Total Capital Installed URDC System	132.2	398.8	1,838.1

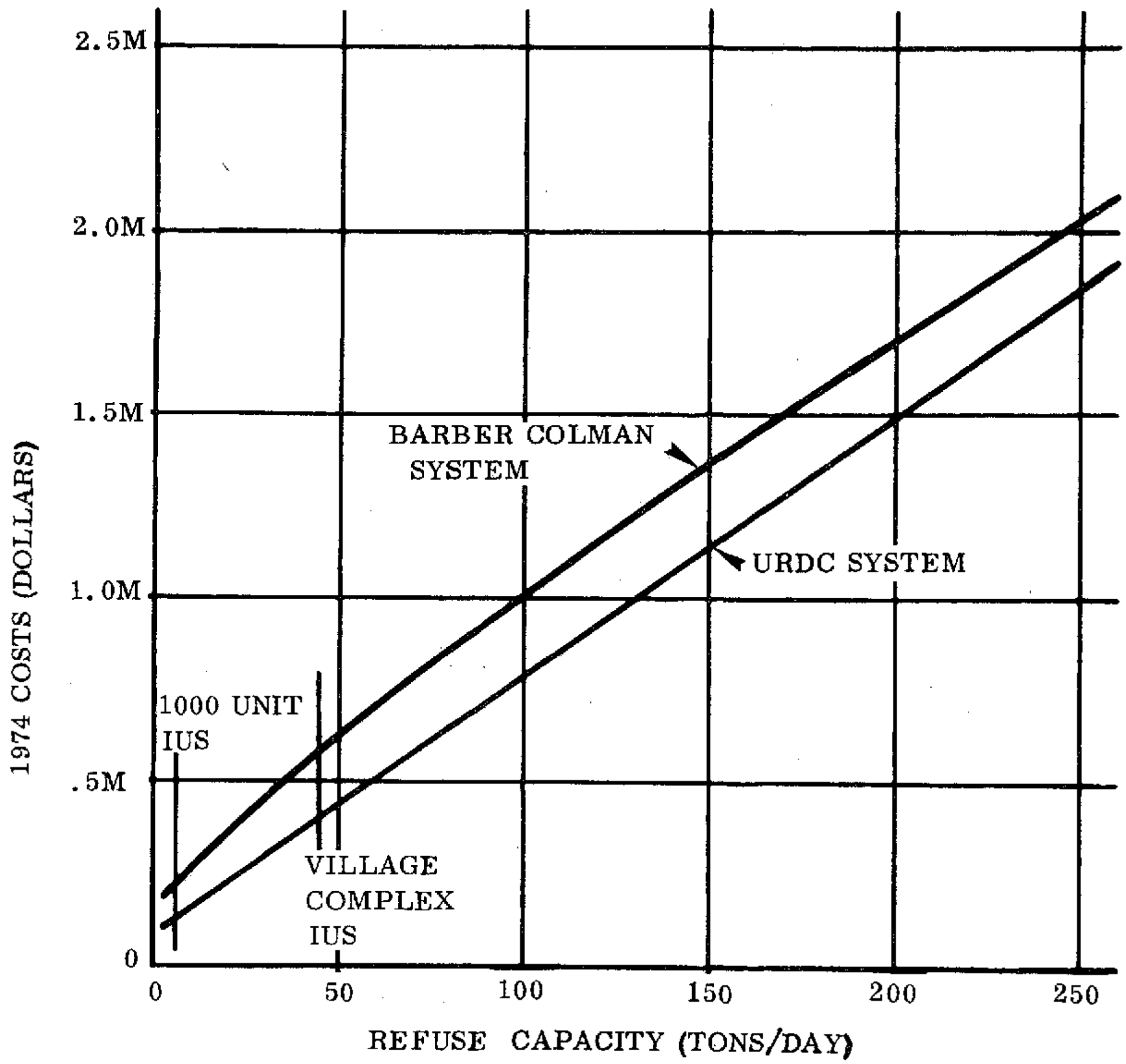


FIGURE 1
PYROLYSIS UTILITY SYSTEMS
CAPITAL COSTS

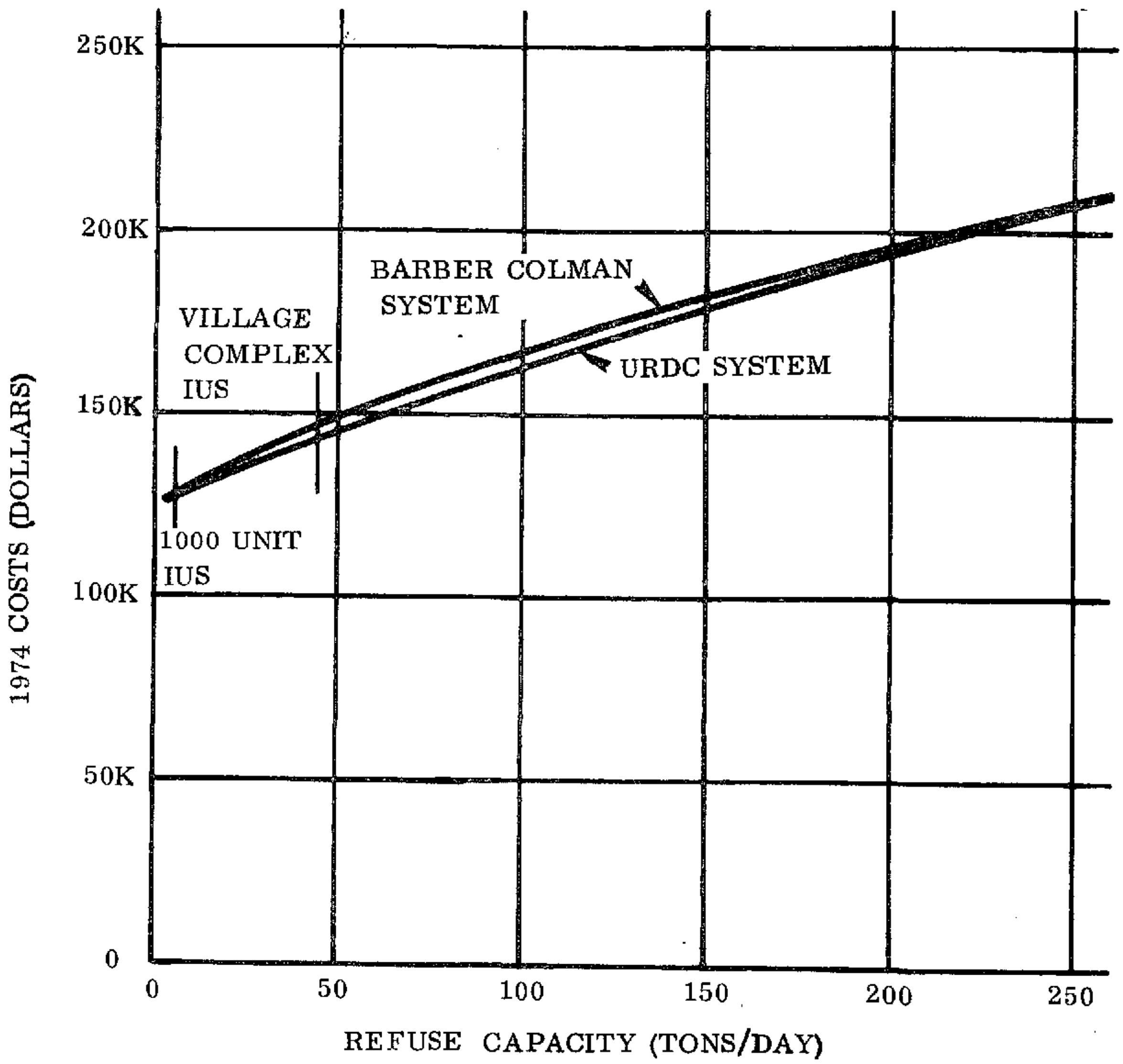
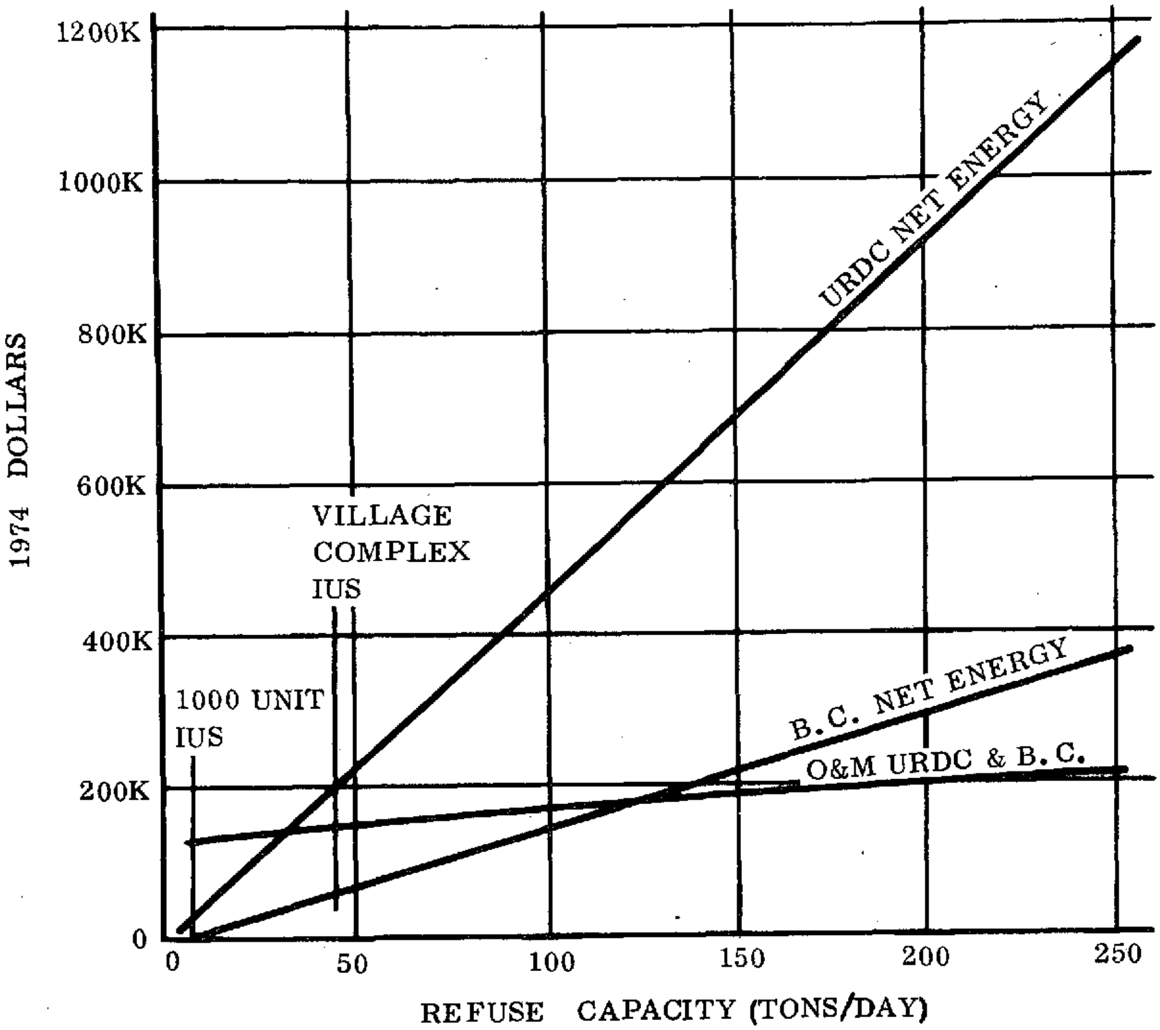


FIGURE 2
ANNUAL OPERATING & MAINTENANCE COSTS
URDC AND BARBER COLMAN
UTILITY PYROLYSIS SYSTEMS



NOTE: NET ENERGY CURVES ARE BASED ON INDICATED REFUSE CAPACITY PLUS SLUDGE CAPACITY. (SLUDGE CAPACITY = .67 X REFUSE)

FIGURE 3
PYROLYSIS UTILITY SYSTEMS
ANNUAL O&M COSTS AND NET ENERGY VALUE
V.S.
REFUSE HANDLING CAPACITY

TABLE 3
URDC PYROLYSIS SYSTEM COMPONENT COSTS

Item No.	Name	Cost 6 TPD	Cost 45 TPD	Cost 250 TPD	Estimating Technique 6 TPD	Estimating Technique 45 TPD	Estimating Technique 250 TPD
201	Storage Carts (100 Required)	45,000	N/A	N/A	Q	--	--
202	Cart Lifter/Dumper	8,000	8,000	18,000	Q	Q	E
203	Loading Ram	6,100	6,100	18,000	Q	Q	Q
204	Pyrolysis Reactor	20,000	107,000	594,000	MQ	SMQ	SMQ
206	Precipitator	1,500	25,000	150,000	Q	Q	Q
207	Wet Scrubber	1,200	7,500	17,000	Q	Q	Q
208	Back Pressure Control System	900	1,000	3,000	Q	E	E
210	Gas Flow Meter	500	500	1,000	E	E	E
211	Excess Gas Burner	1,400	1,500	3,000	Q	E	E
212	Excess Gas Burner Blower	700	3,000	6,100	Q	RQ	RQ
213 214	Slag Quench Tank Slag Conveyer	3,900	3,900	8,000	MQ	MQ	E
215	Wash Cooler	4,500	14,300	28,000	Q	RQ	RQ
216	Wash Pump	800	900	6,700	Q	Q	Q
217	Wash Level Control System	900	900	1,500	Q	Q	E

TABLE 3
(Continued)

Item No.	Name	Cost 6 TPD	Cost 45 TPD	Cost 250 TPD	Estimating Technique 6 TPD	Estimating Technique 45 TPD	Estimating Technique 250 TPD
218	Oxidation Air Blower	600	2,800	5,500	Q	RQ	RQ
220	Oxidation Air Heater	12,000	3,800	75,000	E	Q	Q
221	Oxidation Air Heater Burner	1,000	5,500	8,800	Q	E	E
222	Oxidation Air Heater Burner Blower	300	1,500	3,000	Q	RQ	RQ
223	Reactor Control System	3,200	3,500	10,000	DE	E	E
224	Condensed Oil and Tar Pump	200	200	1,000	Q	Q	E
225	Oxidation Air Heater Auxiliary Burner	1,300	7,000	11,800	Q	E	E
226	Reactor Auxiliary Burner	1,300	7,000	11,800	Q	E	E
227	Hot Gas Blower	800	3,500	7,000	Q	Q	Q
	Total (Excluding Carts)	71,100	214,400	988,200			

Legend: Q = Quote = Letter or Telephone Quote
MQ = Modified Quote = Quote Plus Estimate of Modifications
SMQ = Scaled MQ = MQ Scaled Up for TPD Size
E = Estimate = Best Estimate (Based on 6 TPD Unit when Possible)
RQ = Ratioed Quote = Q Multiplied by Some Known or Calculated Ratio
DE = Detailed Estimate = Based on Estimate of Many Small Items

TABLE 4
SIX TPD URDC SYSTEM INSTALLATION

Component	Component Cost	Installation	Total	Maint.
Cart Lifter/Dumper	$ 8,000	$ 500	$ 8,500	$ 240
Loading Ram	6,100	1,000	7,100	183
Pyrolysis Reactor	20,000	2,600	22,600	1,533
Precipitator	1,500	500	2,000	45
Wet Scrubber	1,200	500	1,700	36
Back Pressure Control System	900	800	1,700	27
Gas Flow Meter	500	300	800	15
Excess Gas Burner	1,400	700	2,100	42
Excess Gas Burner Blower	700	500	1,200	21
Slag Tank and Conveyer	3,900	1,000	4,900	117
Wash Cooler	4,500	400	4,900	135
Wash Pump	800	200	1,000	24
Wash Level Control System	900	100	1,000	27
Oxid. Air Blower	600	400	1,000	18
Oxid. Air Heater	12,000	900	12,900	1,200
Oxid. Air Heater Burner	1,000	600	1,600	30
Oxid. Air Heater Burner Blower	300	400	700	9
Reactor Control System	3,200	5,000	8,200	96

TABLE 4
(Continued)

Component	Component Cost	Installation	Total	Maint.
Condensed Tar and Oil Pump	$ 200	$ 300	$ 500	$ 6
Oxid. Air Heater Auxiliary Burner	1,300	400	1,700	39
Reactor Auxiliary Burner	1,300	400	1,700	39
Hot Gas Blower	800	600	1,400	24
Misc. Installation (25%)	--	3,800	3,800	--
	$71,100	$21,900	$ 93,000	--
Duct and Pipe	2,800		2,800	84
Wire	1,100		1,100	33
Subtotal	$75,000	$21,900	$ 96,900	$4,000
Engineering and Handling (50% of Comp. Cost)			35,500	
Installed System			$132,400	

$$\text{Factor} = \frac{96.9-71.1}{71.1} \times 100 = 36.3\%$$

The Table includes a code to indicate the estimating technique used for each component. The estimating technique code is as follows:

Q - This indicates a firm budgetary quote from the manufacturer of the equipment either by letter or telephone, or a vendor's budgetary quote on a non-standard size unit.

MQ - Represents a manufacturer's quote for a standard item with Hamilton Standard estimates of additional cost due to modification or additions for the specific application.

SMQ - Represents an MQ type quote that has been scaled up or down for size based on separate factors for materials and labor increases.

RQ - This is a ratioed quote and is used when a firm quote (Q) is available for a similar item, and a known size or capacity ratio exists. For example, in the case of pumps and blowers, one pump supplier and one blower supplier offered firm quotes for all three sizes 6, 45 and 250 TPD. The ratio of these numbers was applied to other size pump or blower quotes for 6 TPD units to obtain the corresponding 45 and 250 TPD unit costs.

E - Represents an estimate without specific vendor quote data as back up. In most cases where E is used, a Q or an RQ exists for the 6 TPD size unit but not for larger sizes, and the estimate for these larger sizes was made based on the expected

difference between a 6 TPD unit and that required for a 45 or 250 TPD unit.

DE - Represents the detailed estimate made for the control systems and includes catalog prices on components and cabinets expected to be required for the control function.

Storage carts (201) are not included in the totals, since they apply only to the 6 TPD IUS plant size, and their cost is part of the IUS cost.

The TPD notation applies only to the tons of trash handled by each system and does not include the sewage sludge capabilities of the systems. For example, the equipment specified for the 6 TPD unit has additional capacity to handle 4 TPD of sewage sludge for a total of 10 TPD.

The estimates of installation costs shown in Table 4 for each component were made by an engineer experienced in the construction and facilities field. Site preparation is included in these estimates.

OPERATION AND MAINTENANCE

The estimated operation and maintenance expenses are summarized in Table 5. The major portion of these costs are operator labor charges shown in Table 6 for the 6 and 250 TPD system. The labor costs for the 45 TPD system was estimated on a straight

TABLE 5
URDC PYROLYSIS SYSTEM
ANNUAL OPERATING AND MAINTENANCE COSTS

	URDC O&M		
TPD	6	45	250
Component Cost	$ 71.1	$214.4	$988.2
Labor	$123.0	$131.0	$174.4
Misc. Op. Expense (.5%)	.4	1.1	4.9
Total Operation	$123.4	$132.1	$179.3
Maintenance %	5.6	5.2	2.8
Maintenance Expense	4.0	11.1	27.7
Total O&M	$127.4	$143.2	$207.0

TABLE 6
PYROLYSIS SYSTEMS LABOR EXPENSES

6 TPD System	
1 Skilled Operator	$ 20,000
1 Semi-Skilled Operator	15,000
	$ 35,000
3 Shift Coverage, 6 Days/Week	x 4x6/7
	$120,000
1 Engineer, 10% Time @ $30K/Year	3,000
	$123,000
250 TPD System	
1 Skilled Operator	$ 20,000
2 Semi-Skilled Operators	30,000
	$ 50,000
3 Shifts, 6 Day/Week	x 4x6/7
	$171,400
1 Engineer, 10% Time @ $30K/Year	3,000
	$174,400

line relationship between the 6 and 250 TPD systems. It was assumed that two operators would be a minimum required for any pyrolysis system for safety reasons. This was used for the 6 TPD system, and one additional operator was added for the 250 TPD system.

An estimate of cost for three shift coverage for seven days per week is four men for each position in order to cover vacations, sick time, weekends, etc. Accordingly, the salaries for one shift coverage were factored by 4 x 6/7 for six day operation. An engineer spending 10% of his time is included in the expense. An additional 1/2% of the component costs was included for miscellaneous operating expenses.

Maintenance for the 6 TPD system was estimated by the economic ground rules prepared earlier in the study. This fraction of the total component costs at the 6 TPD system size was assumed to decrease linearly to one-half the value for the 250 TPD system.

NET FUEL GAS PRODUCED

The net fuel gas produced was calculated based on the performance estimate of 2,100 Btu/lb LHV of waste input to the system with the electrical energy consumption deducted based on a generator with electrical conversion efficiency of 35.1% on the LHV. The fuel value was taken at $\$1.85/10^6$ Btu per the study ground rules.

Start up fuel requirements were ignored because they would have a maximum effect of 2% decrease in the net energy produced. Table 7 shows a summary of the net energy for the three system sizes considered.

TABLE 7

ECONOMIC VALUE OF NET ENERGY PRODUCED BY THE URDC PYROLYSIS SYSTEM

System Capacity	(TPD)	6	45	250
Average Electrical Power	(KW)	7.873	53.85	295.8
Annual Electrical Energy	(10^6 BTU)	201.8	1,381	7,584
Fuel Required @ 35.1% Eff.	(10^6 BTU)	574.8	3,933	21,606
Fuel Produced	(10^6 BTU)	15,330	114,975	638,750
Net Fuel	(10^6 BTU)	14,755	111,042	617,144
Net Value of Energy @ $1.85/$10^6$ BTU		$27,297	$205,427	$1,141,716

(Based on 12 TPD refuse and 8 TPD sewage sludge)

APPENDIX B5

POWER SUMMARY FOR URDC PYROLYSIS SYSTEM

POWER SUMMARY FOR URDC PYROLYSIS SYSTEM

The power summary for the URDC Pyrolysis System contained in Table 1 shows the peak power for each major electrical consuming item. A load factor is applied to indicate the amount of time the component is operating for each day of system operation, resulting in an average daily power consumption rate. All sizing is based on 24 hour per day, 6 day per week operation at a plant receiving 6 tons of trash and 4 tons of sewage sludge seven days a week.

URDC POWER SUMMARY

Item No.	Name	Peak Power (KW)	Load Factor	Average Power (KW)
202	Cart Lifter/Dumper	3	2/15	.4
203	Loading Ram	1	2/15	.13
206	Precipitator	1.0	1	1.0
208	Back Pressure Control System	.2	1	.2
212	Excess Gas Burner Blower	2.2	0	0
214	Slag Quench Conveyer	.5	1	.5
216	Wash Pump	1.36	1	1.36
217	Wash Level Control System	.1	1	.1
218	Oxidation Air Blower	2.0	1	2.0
222	Oxidation Air Heater Burner Blower	.32	1	.32
223	Reactor Control System	.5	1	.5
224	Condensed Oil and Tar Pump	.33	.1	.033
225	Oxidation Air Heater Auxiliary Burner	.5	0	0
226	Reactor Auxiliary Burner	.5	0	0
227	Hot Gas Blower	1.33	1	1.33
		14.84		7.873

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION

APPENDIX C1

BARBER-COLMAN PYROLYSIS SYSTEM

COMPONENT SPECIFICATIONS

PARTS LIST-BARBER COLMAN PYROLYSIS SYSTEM

ITEM NO.	NAME
101	Storage Carts
102	Shredder Conveyor
103	Shredder
104	Storage Conveyor
105	Storage Silo
108	Pyrolysis Reactor
111	Back Pressure Control
113	Gas Flow Meter
114	Excess Gas Burner
116	Hot Char Conveyor
130	Wash Level Control
131	Reactor Air Blower
132	Reactor Air Burner (2 required)
133	Reactor Control
138	Oil Skimmer
140	Hot Gas Blower
141	Reactor Feed Conveyor
142	Compactor Screw Conveyor
143	Fume Vent Blower
144	Intake Filter
145	Flue Box After Burner
146	Lead Circulation Pump
147	Wash Water Pump
148	Residue Conveyor
149	Char Flotation Tank
150	Oil and Tar Pump
151	Char Dewatering Separator
152	After Burner Preheat
153	Char Quench Conveyor
154	Gas Scrubber
155	Separator Demister
156	Wash Drain Pump
157	Wash Water Cooler
158	Char Conveyor
159	Char Slurry Pump

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.:	101
Component Name:	Storage Cart
Quantity Required:	100
Operating Fluids:	Type 2 trash

Description (Functional, Concept, Materials, etc.):

Wheeled cart approx. 1 1/2 cu. yd. vol. for dumping trash into shredder conveyor hopper from ground level and collecting residue from char flotation tank.

Performance Requirements:

Front load and unload
Cover hinged
Front of cart to have 45^{o} slope.

Structural Requirements:

Steel welded construction
Handle for pushing
Wheeled (2 stationary, 2 swivel caster)

Electrical Requirements:

N/A

Interface and Envelope Requirements:

74" long, 40 1/2 wide, 44" high

Quantity and Safety Requirements:

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 102

Component Name: Shredder Conveyor

Quantity Required: 1

Operating Fluids: Type 2 trash

Description (Functional, Concept, Materials, etc.):

Belt type conveyor with variable speed motor drive with cleats on belt to prevent roll back of trash.

Performance Requirements:

Convey trash from hopper to shredder at a rate of 14000#/day on demand from shredder
Load capacity - 10#/sq. ft.

Structural Requirements:

30-36" wide

Electrical Requirements:

115/230/460 vac 3/60 Hz
.12 KW avg. power

Interface and Envelope Requirements:

Interface with shredder feed hopper

Quantity and Safety Requirements:

Manual shutoff
Auto shutoff in case of overload
TEFC motor
Automatic fire detection and extinguishing system

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 103

Component Name: Shredder

Quantity Required: 1

Operating Fluids: Type 2 trash

Description (Functional, Concept, Materials, etc.):

Hammer mill type trash shredder to take household rubbish and shred it into 2" size bits.

Performance Requirements:

Input rate = 14,000#/day (10#/cu ft.)
Input size = 2' dia. x 3' long max.
Output size = 2" max. dim.

Structural Requirements:

Mounting platform

Electrical Requirements:

115/230/460 vac
3/60 Hz
75 KW peak, 3.15 KW avg. power

Interface and Envelope Requirements:

Opening for shredder conveyor (102)
Discharge opening for storage conveyor (104)

Quantity and Safety Requirements:

Shield to protect against ejection of ballistic projectiles
Fire safety detection and extinguishing equipment
TEFC motor

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.:	104
Component Name:	Storage Conveyor
Quantity Required:	1
Operating Fluids:	Shredded type 2 trash

Description (Functional, Concept, Materials, etc.):

Belt type conveyor to take shredded trash from shredder to storage silo.

Performance Requirements:

Speed compatible with shredder output
Capacity 14000 #/day
Trash size 2" max. dim.
Lift height 20 ft. Inlet hopper size 25 ft^3

Structural Requirements:

30-36" wide belt, side aprons to prevent spillage
Sheet metal enclosure to be water tight

Electrical Requirements:

113/230/460 VAC
3/60 Hz
2 KW peak 1.2 KW avg. power

Interface and Envelope Requirements:

Enclosure to mate with shredder output (103) and silo input flanges (105)

Quantity and Safety Requirements:

Fire detection and extinguishing equipment
TEFC motor

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 105

Component Name: Storage Silo

Quantity Required: 1

Operating Fluids: Shredded type 2 trash, sewage sludge char, oil and tars

Description (Functional, Concept, Materials, etc.):

Silo to receive and store shredded trash from shredder with capabilities of 2 day output storage

Performance Requirements:

Capacity 1200 cu. ft. below shredder conveyor interface
Bridge breakers to prevent bridging of trash
Controlled output at bottom to prevent overloading of reactor feed conveyor

Structural Requirements:

Self supporting

Electrical Requirements:

N/A

Interface and Envelope Requirements:

Interface with
Storage conveyor (104)
Reactor feed conveyor (141); fume vent blower (143)
Char conveyor (158) and tars and oil line

Quantity and Safety Requirements:

Fire detection and extinguishing equipment

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 108

Component Name: Pyrolysis Reactor

Quantity Required: 1

Operating Fluids: Molten lead, pyrolysis gas, shredded type 2 trash

Description (Functional, Concept, Materials, etc.):

Lead bath transport, radiant tube heated pyrolysis reactor

Performance Requirements:

Reduce shredded trash, char and sewage sludge to a char while liberating gasses and volitized oil and tars

Rate 1114.5 lb/hr total input

880 #/hr gas output

235 #/hr hot char

Temp. range of lead bath 1200 to 1300°F

Structural Requirements:

Carbon steel
Fire brick
Insulation

Electrical Requirements:

N/A

Interface and Envelope Requirements:

Interface with reactor air burner (132) (2)
Interface with lead circulation pump (146)
Interface with compactor screw conveyor (142)
Interface with char quench conveyor (116)
Interface with hot gas blower (140)
Flue box after burner (145)

Quantity and Safety Requirements:

Pressure relief panel

PYROLYSIS SYSTEM
<u>COMPONENT REQUIREMENTS</u>

Item No.: 111

Component Name: Back Pressure Control

Quantity Required: 1

Operating Fluids: Pyrolysis Gas

Description (Functional, Concept, Materials, etc.):

Maintain pressure downstream of reactor to a level above ambient sufficient to prevent leakage of air into combustible gas. Consists of electric actuator driven butterfly valve pressure sensors and elec. controller with dial readout.

Performance Requirements:

0-1 psig pressure sensor
Valve pressure drop .5" H_2O max. at 349.5 #/hr 80^oF pyrolysis gas (.064 #/ft^3)
Press drop range .5 to 20" H_2O

Structural Requirements:

Line mounted valve

Electrical Requirements:

Elec actuator for modulating valve - remote controller 115 vac 1/60 Hz, .2 KW avg. power

Interface and Envelope Requirements:

2" dia pipe flanged inlet and outlet
Electrical connectors on valve actuator and pressure sensors

Quantity and Safety Requirements:

Audiable alarm when gas pressure drops below .5" H_2O
Explosion proof actuator

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 113

Component Name: Gas Flow Meter

Quantity Required: 1

Operating Fluids: Pyrolysis Fuel Gas

Description (Functional, Concept, Materials, etc.):

Gas Meter to measure and record flow rate and quantity of fuel gas delivered.

Performance Requirements:

Total flow readout in ft^3 15×10^6 ft^3 minimum
Flow rate in CFM max 200 CFM resetable
Flow rate 89 CFM ave. temp. 80^oF
Density .0669 #/ft^3 ACFM
$\Delta P = .5''$ H_2O max.

Structural Requirements:

Panel mount for readout meter
Line mount for indicator

Electrical Requirements:

(Power included in 133 reactor control)

Interface and Envelope Requirements:

To be inserted in 3" output line downstream of modulating valve of item (111).

Quantity and Safety Requirements:

Weather proof indicator

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 114

Component Name: Excess gas burner

Quantity Required: 1

Operating Fluids: Raw pyrolysis gas at 2250 Btu LHV air

Description (Functional, Concept, Materials, etc.):

Gas burner and combustion air blower to burn off excess gas not required due to lessened demand or shutoff of equipment using process gas.

Performance Requirements:

Gas flow rate 0-880 #/hr raw process gas
Gas pressure 20" H_2O
Burn tube to reduce visibility and noise

Structural Requirements:

mounting brackets

Electrical Requirements:

115/230/460 VAC 3/60 Hz
2.53 KW power avg. when operating

Interface and Envelope Requirements:

Interface with:
Flue box after burner
Hot gas blower
Air Inlet

Quantity and Safety Requirements:

Sound level <75 d.b.
Spark ignition
Flame safety system

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 116

Component Name: Hot Char Conveyor

Quantity Required: 1

Operating Fluids: Molten Leak, Char

Description (Functional, Concept, Materials, etc.):

Chain drag link conveyor to skim char from lead bath and dump into char quench conveyor

Performance Requirements:

Capacity 235 #/hr (38 cu. in/min)
Temp. 1300°F

Structural Requirements:

Mounted inside reactor

Electrical Requirements:

115/230/460 vac 3/60 Hz
.5 KW avg. power

Interface and Envelope Requirements:

Interface with char quench conveyor
Interface with reactor lead bath

Quantity and Safety Requirements:

TEFC motor

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 130

Component Name: Wash Level Control

Quantity Required: 1

Operating Fluids: Condensate from gas scrubber and separator demister

Description (Functional, Concept, Materials, etc.):

Level control system consisting of 4 water level sensors, 3 elect. servo valves and a master controller to control level of char flotation tank (149) gas scrubber (154) separator demister (155) char dewatering separator (151)

Performance Requirements:

Control valves
5" H_2O pressure drop max at 180 gpm full open position

Structural Requirements:

Seal tight connection into line mounted valves and level sensing areas

Electrical Requirements:

110/208 VAC
100 watt avg. power

Interface and Envelope Requirements:

Flange interface at level sensing areas
2 1/2" pipe flange on valves

Quantity and Safety Requirements:

Weather proof valve actuators and sensors

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 131

Component Name: Reactor Air Blower

Quantity Required: 1

Operating Fluids: Ambient air

Description (Functional, Concept, Materials, etc.):

Centrifugal blower to provide air for reactor air burners

Performance Requirements:

Air flow	950.0 CFM (4346.5 #/hr)
Static Press.	12" H_2O
RPM	3600

Structural Requirements:

Mounting Bracket

Electrical Requirements:

113/230/460 VAC 3/60 Hz
3.26 KW avg. power

Interface and Envelope Requirements:

Interface with intake filter (144)and reactor air burners (132)

Quantity and Safety Requirements:

Sound level <75 DB
TEFC motor
Filter Muffler Req'd. (see item 144)

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PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 132

Component Name: Reactor Air Burner

Quantity Required: 2

Operating Fluids: Fuel oil, air fuel gas

Description (Functional, Concept, Materials, etc.):

Dual fuel burner to heat reactor thru radient tubes. Start up with fuel oil and run with fuel gas. Spark ignition

Performance Requirements:

Fuel oil flow rate 2.1 g/h (140,000 Btu/gal)
Fuel gas flow rate 130.2 #/hr. (2250 Btu/#)
Air capacity - 475 CFM
Air Temp in 60^{o}
Hot gas temp. out 2500^{o}

air pressure in 12 " H_2O

Structural Requirements:

Flange mounted

Electrical Requirements:

110/208 vac
Spark ignition

Interface and Envelope Requirements:

Interface with pyrolysis reactor radiant tubes (108) and reactor air blower (131)

Quantity and Safety Requirements:

Flame safety system
and Auto shut down

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 133

Component Name: Control Reactor

Quantity Required: 1

Operating Fluids: N/A

Description (Functional, Concept, Materials, etc.):

Console to control reactor temp. fuel and air flow rates and to provide reactor operating data.

Performance Requirements:

Maintain reactor outlet gas temp. at 800°F
Maintain reactor lead bath temp. at 1300°F
Read 2 temp, 2 pressures and 1 flow rate in system

Structural Requirements:

Console type enclosure

Electrical Requirements:

115/230/460 VAC 3/60 H_Z
.5 KW avg power

Interface and Envelope Requirements:

Elec. conduct interface with components

Quantity and Safety Requirements:

Electrical grounding
O.S.H.A. Panel and enclosure

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 138

Component Name: Oil Skimmer

Quantity Required: 1

Operating Fluids: Condensate from gas scrubber and separator demister (H_2O, HCL, NH_3 H_2S, Tars and oil)

Description (Functional, Concept, Materials, etc.):

Part of char flotation tank that removes oils and tars from condensate for return to reactor

Performance Requirements:

Capacity 90,400 #/hr liquor
24 #/hr oil

Structural Requirements:

Part of char flotation tank

Electrical Requirements:

N/A

Interface and Envelope Requirements:

Interface with wash drain pump (156)
Interface with oil and tars pump (150)
Interface with char flotation tank (149)

Quantity and Safety Requirements:

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 140

Component Name: Hot Gas Blower

Quantity Required: 1

Operating Fluids: Pyrolysis Gas

Description (Functional, Concept, Materials, etc.):

Stainless steel centrifugal blower to move pyrolysis gas from reactor through scrubber and demister then out of system.

Performance Requirements:

Gas temp 800°F
Gas flow 880 #/hr raw fuel gas
Pressure in 1-2" H_2O
Pressure out 10" H_2O

Structural Requirements:

Mounting bracket

Electrical Requirements:

115/230/460 VAC 3/60 Hz
2.39 KW avg. power

Interface and Envelope Requirements:

6" pipe flange inlet and outlet
Interface with pyrolysis reactor (108)

Quantity and Safety Requirements:

Sound level $<$75 db
TEFC motor

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 141

Component Name: Reactor Feed Conveyor

Quantity Required: 1

Operating Fluids: Shredded trash, sewage sludge, tars and oil char

Description (Functional, Concept, Materials, etc.):

Screw type conveyor to receive trash etc. from storage silo and deliver that trash to compactor screw conveyor

Performance Requirements:

Loading 1115.5 #/hr
Vert lift 10' max.

Structural Requirements:

Support structure
Water tight enclosure

Electrical Requirements:

115/230/460 vac 3/60 Hz
3 KW ave. power

Interface and Envelope Requirements:

Interface with storage silo (105)
Interface with compactor screw conveyor (142)
Interface with fume vent blower (143)

Quantity and Safety Requirements:

TEFC motor

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 142

Component Name: Compactor Screw Conveyor

Quantity Required: 1

Operating Fluids: Shredded trash, sewage sludge, char, tars and oil

Description (Functional, Concept, Materials, etc.):

Screw type conveyor receives trash etc. from reactor feed conveyor then compacts and carries trash to reactor.

Performance Requirements:

Loading 115 #/hr
Approx. 6' long horiz mtg.
Screw dia. entrance 9"
Screw dia. exit 6"

Compaction force = 35 psi

Structural Requirements:

Support brackets
Sealed access ports
Completely closed

Electrical Requirements:

115/230/460 V 3/60 Hz
2 KW avg. power

Interface and Envelope Requirements:

Interface with reactor feed conveyor (141)
Interface with pyrolysis reactor feed shute (108)

Quantity and Safety Requirements:

TEFC motor

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 143

Component Name: Fume Vent Blower

Quantity Required: 1

Operating Fluids: Air, Noxious Fumes

Description (Functional, Concept, Materials, etc.):

Centrifugal blower to vent storage silo and reactor feed conveyor of noxious fumes and gasses

Performance Requirements:

Flow rate 500 CFM
Inlet pressure ambient
Outlet pressure 3" H_2O
Gas Temp. $70^{\circ}F$

Structural Requirements:

Mounting Bracket
3" inlet flange
3" outlet flange

Electrical Requirements:

115/230/460 V 3/60 Hz
.43 KW average power

Interface and Envelope Requirements:

Interface with storage silo (105)
Interface with reactor feed conveyor (141)
Interface with flue box after burner (145)

Quantity and Safety Requirements:

Sound level $<$75 DB
TEFC motor
Closed and sealed ducts

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 144

Component Name: Intake Filter

Quantity Required: 1

Operating Fluids: Ambient Air

Description (Functional, Concept, Materials, etc.):

Removable screen type filter positioned so that fumes from trash input hopper are drawn thru filter when reactor air burner is on.

Performance Requirements:

Size 24" x 24" clear opening
1/8" sq. mesh screen

Structural Requirements:

Free standing bracket
Removable filter screen

Electrical Requirements:

N/A

Interface and Envelope Requirements:

Interface with inlet of reactor air blower (131)

Quantity and Safety Requirements:

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 145

Component Name: Flue Box After Burner

Quantity Required: 1

Operating Fluids: Combustion gasses from reactor air burner, gasses from fume vent blower, and combustion gasses from excess gas burner.

Description (Functional, Concept, Materials, etc.):

Fire box to receive combustion gasses and fumes from reactor air burner, excess gas burner and fume vent blower and exhaust to atmosphere after heating in after burner.

Performance Requirements:

4600 #/hr combustion products @ 2000°F and
2280 #/hr air and fumes at 60°F continuously
plus 6660 #/hr combustion products @ 2500°F when excess gas burner is operating

Structural Requirements:

Fire brick lining of fire box
Insulated fully
Stack to carry gasses into atmosphere

Electrical Requirements:

N/A

Interface and Envelope Requirements:

Interface with fume vent blower (143)
Interface with radiant heating tubes from reactor (108)
Interface with after burner preheat (152)
Interface with excess gas burner exhaust (114)

Quantity and Safety Requirements:

Insulation around shell

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 146

Component Name: Lead Circulation Pump

Quantity Required: 1

Operating Fluids: Molten Lead @ 1200 to 1300°F

Description (Functional, Concept, Materials, etc.):

Centrifugal pump to recirculate lead from lead bath in reactor

Performance Requirements:

Flow rate 115.2 cu. in./min.
Head 1 psi
Operating temp. 1000-1200°F

Structural Requirements:

Mounting bracket or flange

Electrical Requirements:

115/230/460 VAC 3/60 Hz
2 KW ave. power

Interface and Envelope Requirements:

Interface with inlet and outlet of pyrolysis reactor (108)

Quantity and Safety Requirements:

Steam jacketed bearings
Insulation
TEFC motor

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 147

Component Name: Wash Water Pump

Quantity Required: 1

Operating Fluids: Water from char dewatering separator

Description (Functional, Concept, Materials, etc.):

Centrifugal pump to recirculate water thru system as required

Performance Requirements:

Flow rate 180 gpm
Temp $80^{o}F$
Discharge pressure 30 psi
Inlet pressure ambient

Structural Requirements:

Foot mounted with motor

Electrical Requirements:

115/230/460 VAC 3/60 Hz
4.56 KW avg. power

Interface and Envelope Requirements:

Interface with wash water cooler (157)
Interface with char dewatering separator (151)

Quantity and Safety Requirements:

TEFC motor

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 148

Component Name: Residue Conveyor

Quantity Required: 1

Operating Fluids: Water, residue from char flotation tank

Description (Functional, Concept, Materials, etc.):

Screw type conveyor of sufficient length to allow drain off of water and carry residue to discharge into storage carts

Performance Requirements:

Load 187.5 #/hr
Volume 18.75 cu ft/hr
5 ft vert lift

Structural Requirements:

Enclosed structure

Mounting stand

Electrical Requirements:

115/230/460 vac 3/60 Hz

1 KW ave. power

Interface and Envelope Requirements:

Interface with char flotation tank (149)

Quantity and Safety Requirements:

TEFC motor

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 149

Component Name: Char Flotation Tank

Quantity Required: 1

Operating Fluids: Water, char, tars, oil, residue

Description (Functional, Concept, Materials, etc.):

Steel tank with agitator to accept discharge of material from pyrolysis reactor after quench. Separate char and incombustable material

Performance Requirements:

Water flow rate 90,400 #/hr
Mixed input 235 #/hr
Residue out 187.5 #/hr
Char out thru char slurry pump 47.5 #/hr (in 90, 400#/hr water)

Structural Requirements:

Water tight with access covers

Electrical Requirements:

115/230/460 VAC 3/60 Hz
.33 kw avg. power

Interface and Envelope Requirements:

Interface with oil skimmer (138)
Interface with char quench conveyor (153)
Interface with residue conveyor (148)
Interface with char slurry pump (129)

Water drain and fill ports

Quantity and Safety Requirements:

TEFC motor

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 150

Component Name: Oil and Tar Pump

Quantity Required: 1

Operating Fluids: Residual oils and tars

Description (Functional, Concept, Materials, etc.):

Positive displacement pump to pump residual oil and tar from oil skimmer back to storage silo.

Performance Requirements:

Req'd. capacity 24 #/hr
Head 40 ft H_2O
Temp. 80-100^{o}F

Structural Requirements:

Mounting feet

Electrical Requirements:

115/230/460 vac. 3/60
.5 KW peak .05 avg. power

Interface and Envelope Requirements:

Interface with oil skimmer (138)
Interface with storage silo (105)

Quantity and Safety Requirements:

TEFC motor

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 151

Component Name: Char Dewatering Separator

Quantity Required: 1

Operating Fluids: Char, water, gravel bed

Description (Functional, Concept, Materials, etc.):

Filter based tank to separate solid char from char/water slurry

Performance Requirements:

Water flow rate 90,400 #/hr
Solid char entrainment 47.5 #/hr

Structural Requirements:

Mounting Base

Electrical Requirements:

N/A

Interface and Envelope Requirements:

Interface with char conveyor (158)
Interface with char slurry pump (159)
Interface with wash water pump (147)

Quantity and Safety Requirements:

Clean out drains

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 152

Component Name: After Burner Preheat

Quantity Required: 1

Operating Fluids: #2 fuel oil, air

Description (Functional, Concept, Materials, etc.):

Fuel oil burner to preheat flue box after burner

Performance Requirements:

100,000 Btu/hr
Preheat flue box after burner prior to start up of reactor burner

Structural Requirements:

Mounting flange for face mounting

Electrical Requirements:

115/230/460 VAC 3/60 Hz
.13 KW peak 0 KW avg. power

Interface and Envelope Requirements:

Interface with flue box after burner (145)

Quantity and Safety Requirements:

Sound level <75 DB
Flame safety system
Spark ignition

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 153

Component Name: Char Quench Conveyor

Quantity Required: 1

Operating Fluids: Water Steam hot char

Description (Functional, Concept, Materials, etc.):

Screw type conveyor to receive hot char from reactor, reduce its temp. to $90^{o}F$ and convey char and residue to char flotation tank.

Performance Requirements:

Capacity 235 #/hr of char residue
Vert lift 5 ft.

Structural Requirements:

Water tight construction

Electrical Requirements:

115/230/460 VAC 3/60 Hz
1 KW avg. power

Interface and Envelope Requirements:

Interface with hot char conveyor (116)
Interface with water feed line
Interface with char flotation tank (149)

Quantity and Safety Requirements:

TEFC motor

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 154

Component Name: Gas Scrubber

Quantity Required: 1

Operating Fluids: Pyrolysis Gas @ 800°F Water @ 70°F

Description (Functional, Concept, Materials, etc.):

Packed tower scrubber to reduce temp. of gas from 800°F and remove H_2O hydrocarbons and other particulates.

Performance Requirements:

Gas inlet temp 800°F
Gas outlet temp. 100°F
Water temp. in 70°F
Water temp. out 80°
Gas press. drop 3-5" H_2O

Gas flow in 880 #/hr
Gas press in 10" H_2O
Water rate 87,900 #/hr
Gas density .07

Structural Requirements:

Gas inlet 6" flanged
Gas outlet 6" flanged
Self support structure

Water in 1" NPT
Water out 2 1/2" NPT

Electrical Requirements:

N/A

Interface and Envelope Requirements:

Interface with hot gas blower (140)
Interface with separator demister (155)
Interface with water inlet and outlet

Quantity and Safety Requirements:

Pressure Relief Panel

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 155

Component Name: Separator - Demister

Quantity Required: 1

Operating Fluids: Scrubbed pyrolysis gas, water

Description (Functional, Concept, Materials, etc.):

Centrifgual separator to remove entrained liquids from pyrolysis gas and reduce temp. from 100°F to 80°F

Performance Requirements:

Gas temp. in 100°F
Gas temp. out 80°F
Water temp. in 70°F
Water Temp. out 80°F
Pressure in 5"-7" H_2O

Water flow rate 2,500 #/hr
Gas flow in 362 #/hr
Gas flow out 349.5 #/hr
Press drop 3"-5" H_2O

Structural Requirements:

Self supporting structure

Electrical Requirements:

N/A

Interface and Envelope Requirements:

Interface with gas scrubber (154)
Interface with back pressure control system (111)

Quantity and Safety Requirements:

Pressure Relief Panel

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 156

Component Name: Wash Drain Pump

Quantity Required: 1

Operating Fluids: Waste water and condensate from gas scrubber and separator demister

Description (Functional, Concept, Materials, etc.):

Centrifugal pump to pump waste water and condensate from gas scrubber and separator demister to oil skimmer.

Performance Requirements:

Volume 90,400 #/hr (180 gpm)
Pressure out 1-2 psi
Pressure in ambient
Water temp. 80-100°F

Structural Requirements:

Mounting feet

Electrical Requirements:

115/230/460 vac 3/60 Hz
.5 KW avg power

Interface and Envelope Requirements:

Interface with oil skimmer (138)
Interface with gas scrubber drain (154)
Interface with separator demister (155)

Quantity and Safety Requirements:

TEFC motor

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 157

Component Name: Wash Water Cooler

Quantity Required: 1

Operating Fluids: Shell side industrial water
Tube side wash water from char dewatering separator

Description (Functional, Concept, Materials, etc.):

Tube and shell heat exchanger to cool recirculating water from 80°F to 70°F

Performance Requirements:

Tube Side	flow - 90,4000 #/hr (180 gpm) temp in 80°F temp out - 80°F	Pressure in 30 psig Pressure out 25 psig
Shell Side	temp in - 70°F temp. out - 80°F	

Structural Requirements:

Counter flow type H/E
Removable ends
Mounting feet

Electrical Requirements:

N/A

Interface and Envelope Requirements:

All interfaces 3" pipe flanges

Quantity and Safety Requirements:

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 158

Component Name: Char Conveyor

Quantity Required: 1

Operating Fluids: Char, water

Description (Functional, Concept, Materials, etc.):

Screw type conveyor to transport char from char dewatering separator to storage silo

Performance Requirements:

Load 47.5 #/hr
Vert lift 10 ft

Structural Requirements:

Water tight interface with char dewatering separator
Support structure

Electrical Requirements:

115/230/460 vac 3/60 Hz
1 KW avg. power

Interface and Envelope Requirements:

Interface with char dewatering separator (151)
Interface with storage silo (105)

Quantity and Safety Requirements:

TEFC motor

PYROLYSIS SYSTEM
COMPONENT REQUIREMENTS

Item No.: 159

Component Name: Char Slurry Pump

Quantity Required: 1

Operating Fluids: Char, water

Description (Functional, Concept, Materials, etc.):

Centrifugal pump to pump char slurry from char flotation tank to char dewatering separator

Performance Requirements:

Flow rate 90,4000 #/hr
Pressure in ambient
Pressure out 5-10 psig

Structural Requirements:

Mounting feet

Electrical Requirements:

115/230/460 VAC 3/60 Hz
1 KW avg. power

Interface and Envelope Requirements:

Interface with char flotation tank (149)
Interface with char dewatering separator (151)

Quantity and Safety Requirements:

TEFC motor

APPENDIX C2

BARBER COLMAN PYROLYSIS SYSTEM SKETCHES

C2

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION

BARBER COLMAN PYROLYSIS SYSTEM DRAWINGS AND SKETCHES

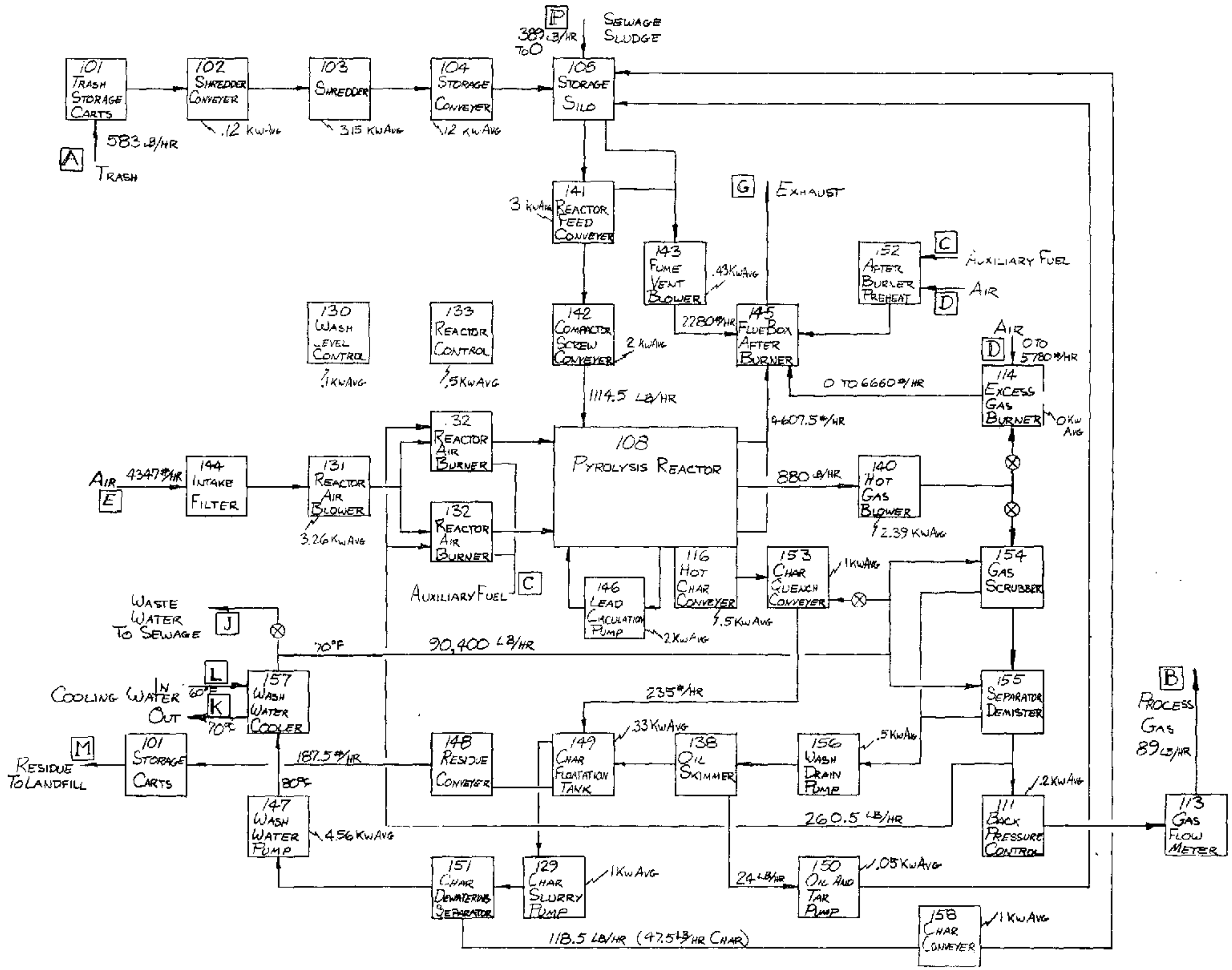
To assist in the understanding of the Barber Colman System as evaluated in this study, Hamilton Standard has generated a block diagram and system sketches of the Barber Colman Pyrolysis System configured for integration into an IUS. Since information available to Hamilton Standard on the Barber Colman design was limited, the details may vary from Barber Colman's current intent; however, Hamilton Standard believes that these drawings accurately reflect the general implementation of the Barber Colman design concept.

Drawings presented are:

Figure 1 - Barber Colman Pyrolysis System Block Diagram

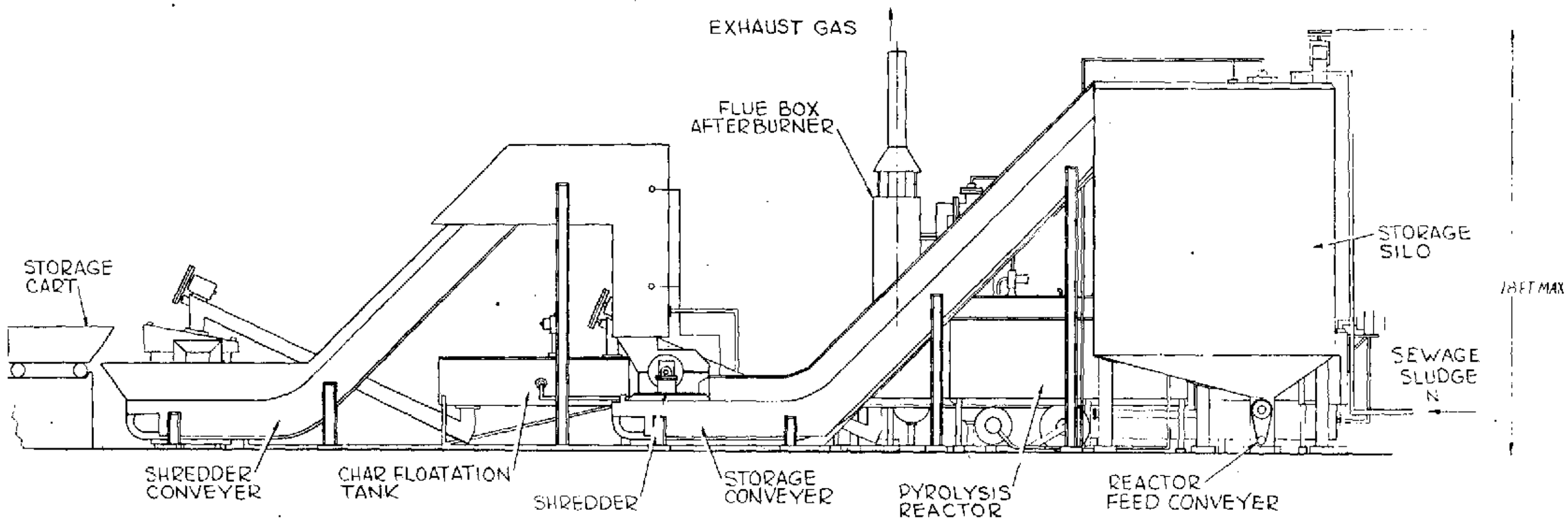
Figure 2 - Barber Colman Pyrolysis System Elevation

Figure 3 - Barber Colman Pyrolysis System Plan View



Barber-Colman Pyrolysis System Block Diagram

FIGURE 1



Barber-Colman Pyrolysis System Elevation

FIGURE 2

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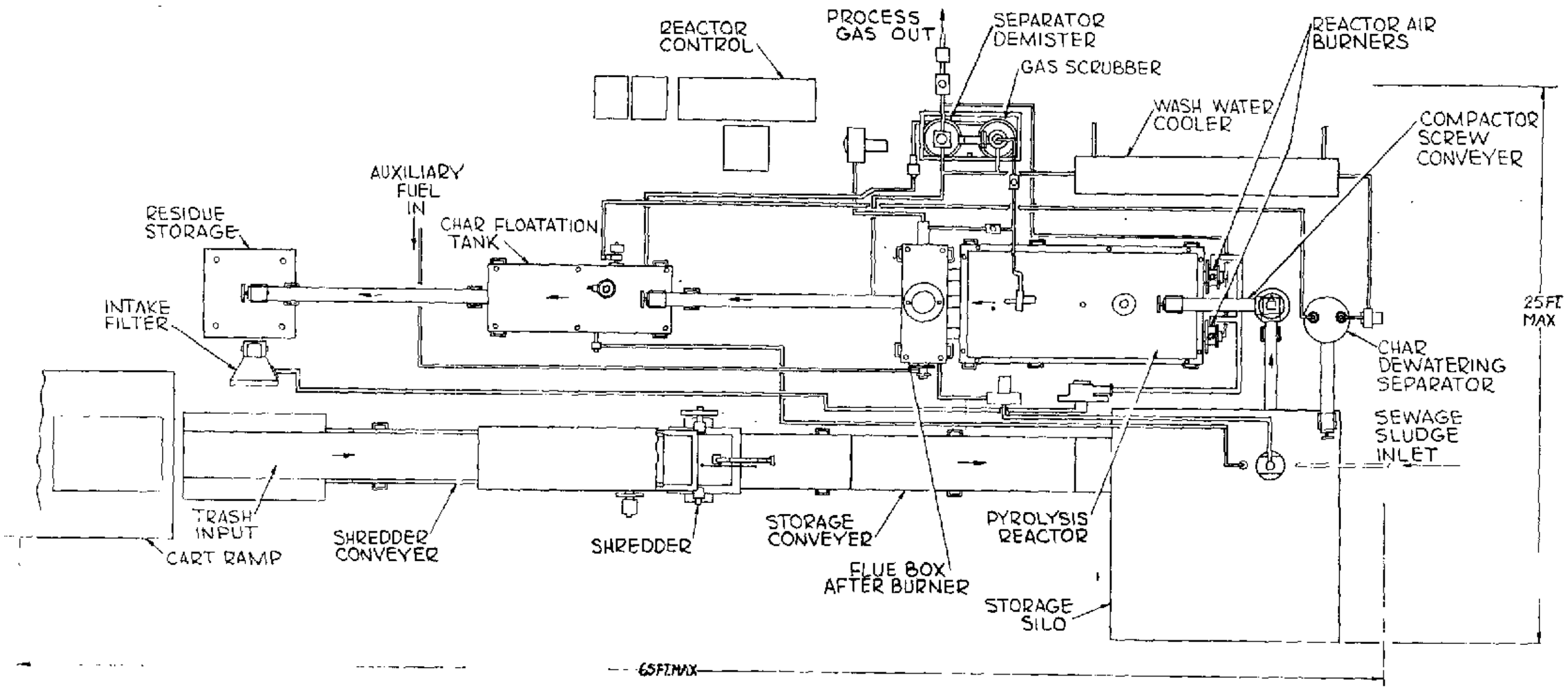


Barber-Colman Pyrolysis System Plan View

FIGURE 3

APPENDIX C3

PERFORMANCE CALCULATIONS

FOR THE BARBER-COLMAN PYROLYSIS SYSTEM

PERFORMANCE CALCULATIONS FOR THE BARBER-COLMAN PYROLYSIS SYSTEM

Basic product distribution characteristics were obtained by proportioning values given in the Barber-Colman block diagram (drawing No. RRS-0100, dated October 1974) which is for a 1,500 lb/hr system feeding typical refuse. The numbers given were proportioned to the corresponding values for one pound of IUS waste feed, assuming that typical refuse is 25% water, 25% inerts, and 50% combustibles. The resulting product distribution is:

Waste Feed	1.000 Lbs
Char Produced	.052
Total Water in Raw Gas	.640 (Air Oxidation of Char)
	.530 (Steam Oxidation of Char)
Tars and Oils	.025

Based on information received and discussions at the technical reviews, the following additional assumptions were made:

- Temperature of gas leaving furnace - 800°F
- Residue discharge temperature (furnace temperature) - 1,300°F
- Heat transferred from radiant tubes to furnace - 50% of burner input
- Char lost with inerts - 5%
- Water in recycled char - 60% (40% solids)

Next, a critical assumption was made: that char could be recycled to extinction in one pass through the furnace (i.e., that recycling the char produced would not increase char production from that which would be obtained without char recycle). This would appear to be a rather optimistic assumption since it is not clear that char oxidation by steam would occur at a high enough rate under the furnace conditions postulated.

Two mechanisms for the gasification of char were postulated: partial oxidation by air (Case 1) and partial oxidation by steam (Cases 2 and 3). In all cases, char oxidation was assumed to occur completely independently of the basic pyrolysis process. Also assumed for all cases was a CO/CO_2 ratio of one for the char oxidation product (this is quite similar to the CO/CO_2 ratio given in the Barber-Colman test data).

The following then are the alternative reactions assumed for char oxidation:

$$(C+0.75O_2+2.82N_2)_{60^oF} \rightarrow (0.5CO+0.5CO_2+2.82N_2)_{800^oF}+7{,}260 \text{ Btu/Lb Char}$$

$$(C+1.5H_2O)_{60^oF}+5180 \text{ Btu/Lb Char} \rightarrow (0.5CO+0.5CO_2+1.5H_2)_{800^oF}$$

In order to allow an estimate of fuel gas scrubber requirements, the following assumptions were made for the inorganic gas phase constituents.

- Half of the nitrogen in the waste would show up as NH_3 in the raw gas.

- The sulfur would show up as H_2S.
- The chlorine would show up as HCl.

These are the same assumptions as were made for the URDC system calculation.

Case 1 and Case 2 represent Barber-Colman's estimate of the system performance corrected to IUS conditions and char recycle. Case 1 is for air oxidation, and Case 2 is for steam oxidation of char. The furnace heat requirements can be summarized as follows:

	Case 1		Case 2
Pyrolysis (0.34)(1000) =	340		340
Char Oxid. (0.049)(-7260) =	-356	(0.049)(5180) =	254
Heat Residue (0.242)(0.2)(1300-60) =	60		60
Boil and Superht. Input Water (0.47+0.073)(1405) =	763		763
Heat Loss (225)(320)/(1500) =	48		48
Total Furnace Heat Required	855 Btu		1,465 Btu

Case 3 is Hamilton Standard's/K. T. Lear Associates' best guess at the mass and energy balance for char oxidation by steam taking the basic assumptions discussed above as givens. One small change in the valves used is that water formation was taken from Bureau of Mines test data (RI 7428) for the case with

gas composition closest to Barber-Colman's valves. The pyrolysis reaction is assumed to be the following:

$$(1 \text{ Lb Combustibles})_{60^oF} + 100 \text{ Btu} \rightarrow (1 \text{ Lb Pyrolysis Vapor+Char})_{60^oF}$$

No further gas/gas or gas/solid reactions are allowed except for char oxidation by steam. The heat required by the furnace must then be equal to the heat of pyrolysis, the heat required for char oxidation, the heat required to raise reaction <u>products</u> to their temperature state at removal from the furnace, plus any furnace heat losses. Assuming that one-half of the tars and oils behave as char, the other half as ordinary waste, the results can be summarized as follows.

Pyrolysis:	
100 Btu/Lb (0.34 + 0.025/2) Lb =	35
Char Oxid.:	
(18,100 Btu/Lb Prod. - 14,000 Btu/Lb React.)	
(0.049 + 0.025/2) Lb =	250
Raw Gas Sensible Heat:	
(0.516 Lb H_2O)(0.47)(800-60) =	180
(0.025 Lb T&O)(0.45)(800-60) =	10
(0.364 Lb Gas)(0.48)(800-60) =	130
Residue Sensible Heat:	
(0.242 Lb)(0.2)(1300-60) =	60
Vaporize Input H_2O:	
(0.47 + 0.073)(1060 Btu/Lb) =	575

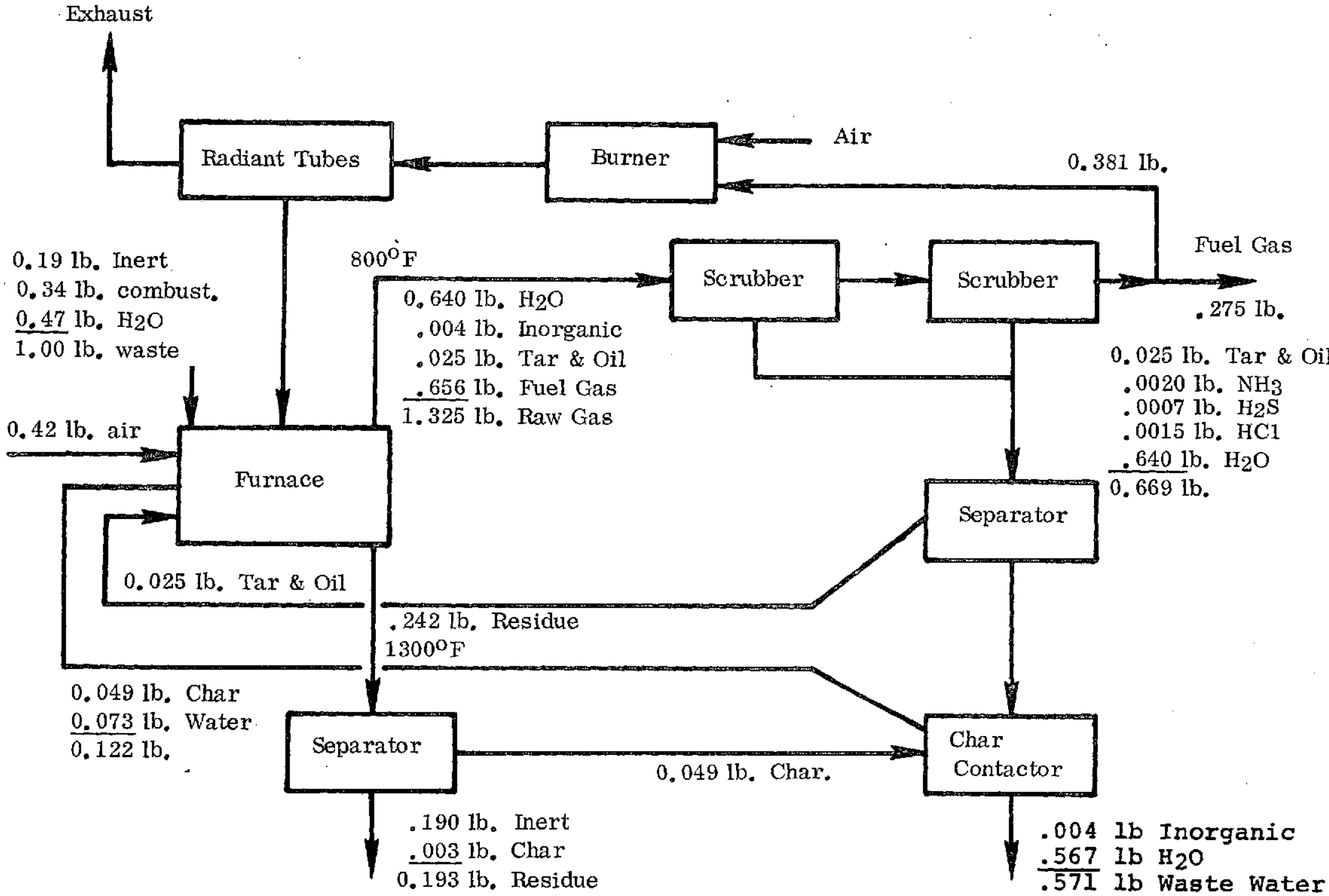
Furnace Heat Loss:

$(225 \text{ Btu/Hr-Ft}^2)(320 \text{ Ft}^2)/(1500 \text{ Lb/Hr}) =$ 50

Total Furnace Heat Required: 1,290 Btu

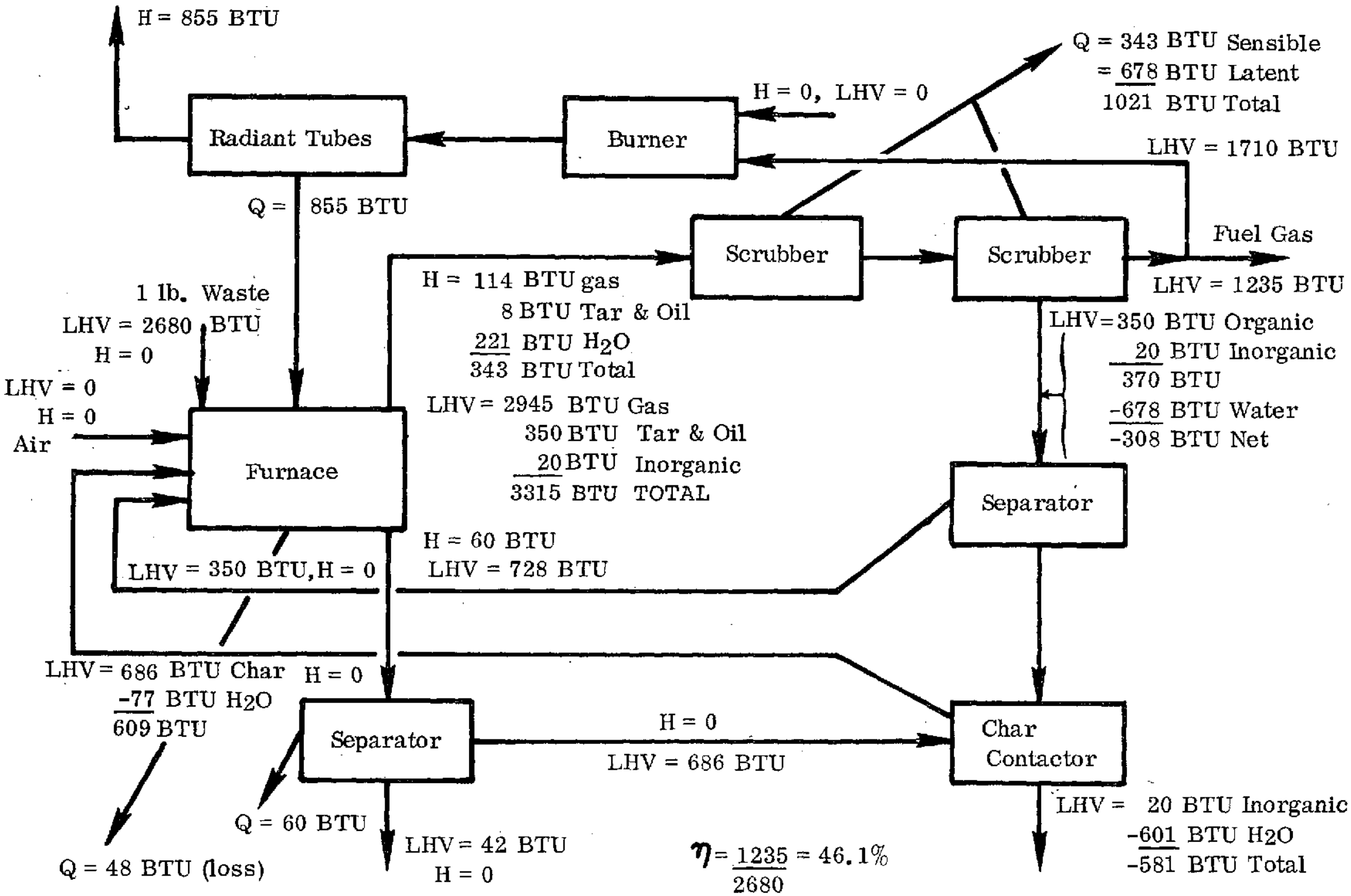
An alternative approach to the energy balance using the same basic assumptions gives a value of 1,250 Btu. The difference is due to small inconsistencies in the individual heats of reaction. The main source is in that the tars and oils were treated as half char and half combustibles which implies a slightly lower LHV than the 14,000 Btu/lb otherwise assumed. The 1,290 Btu result shown above is more internally consistent and probably, therefore, a better value. However, the 1,250 Btu value was used to produce the most optimum projections for the Barber-Colman system.

The mass and energy balances resulting from the three cases described are given in Figures 1 through 6. The net output for the three cases is shown in Table 1. (Electrical power consumption is not included). Case 1 (air oxidation) has significantly better efficiency than the others, but it achieves this at the expense of nitrogen dilution. As expected, the air required to oxidize char is not much different than the air required in a fixed bed gasifier. This can be seen from the resultant fuel gas composition given in Table 2.



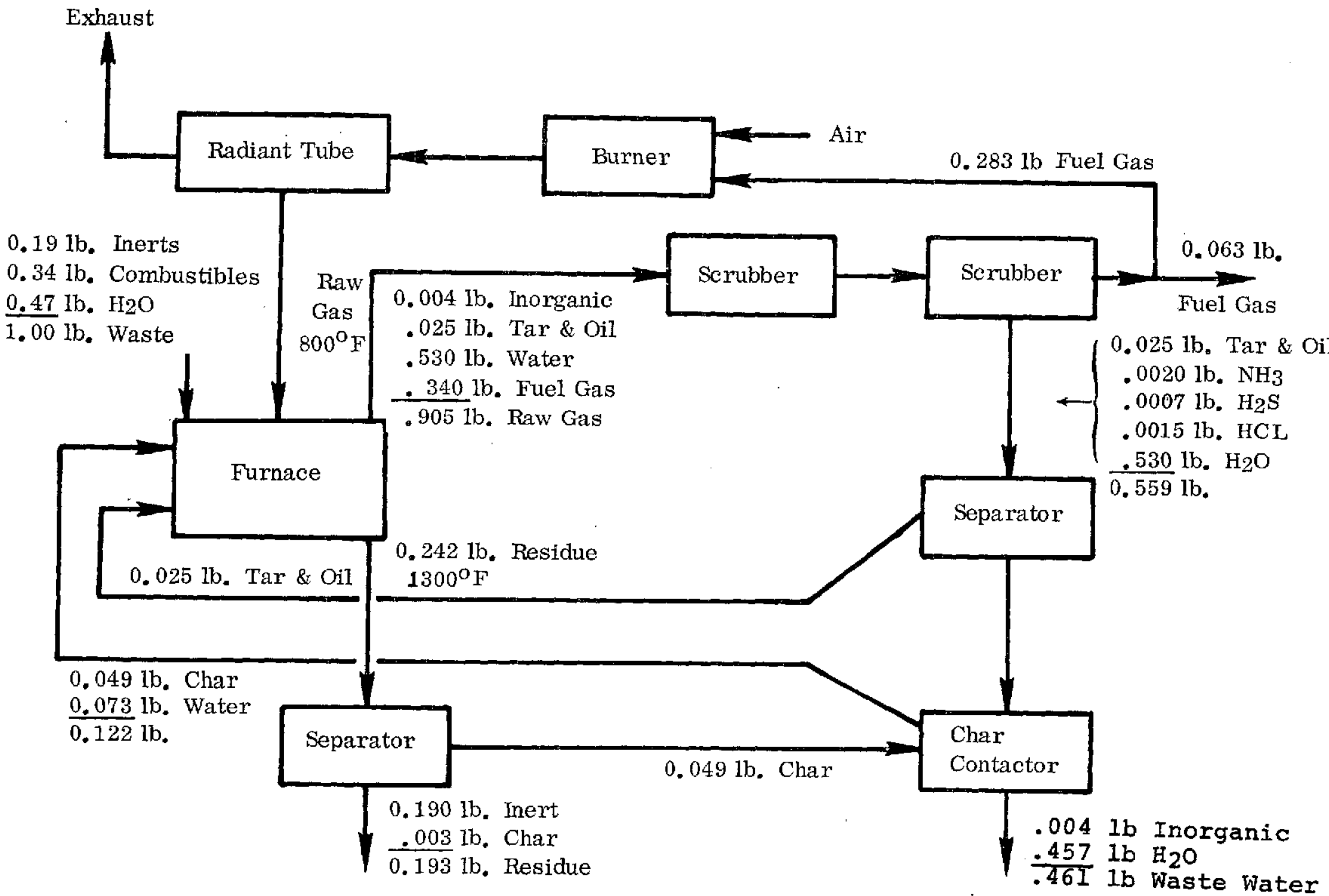
Barber Colman Pyrolysis System Mass Balance Case 1

FIGURE 1



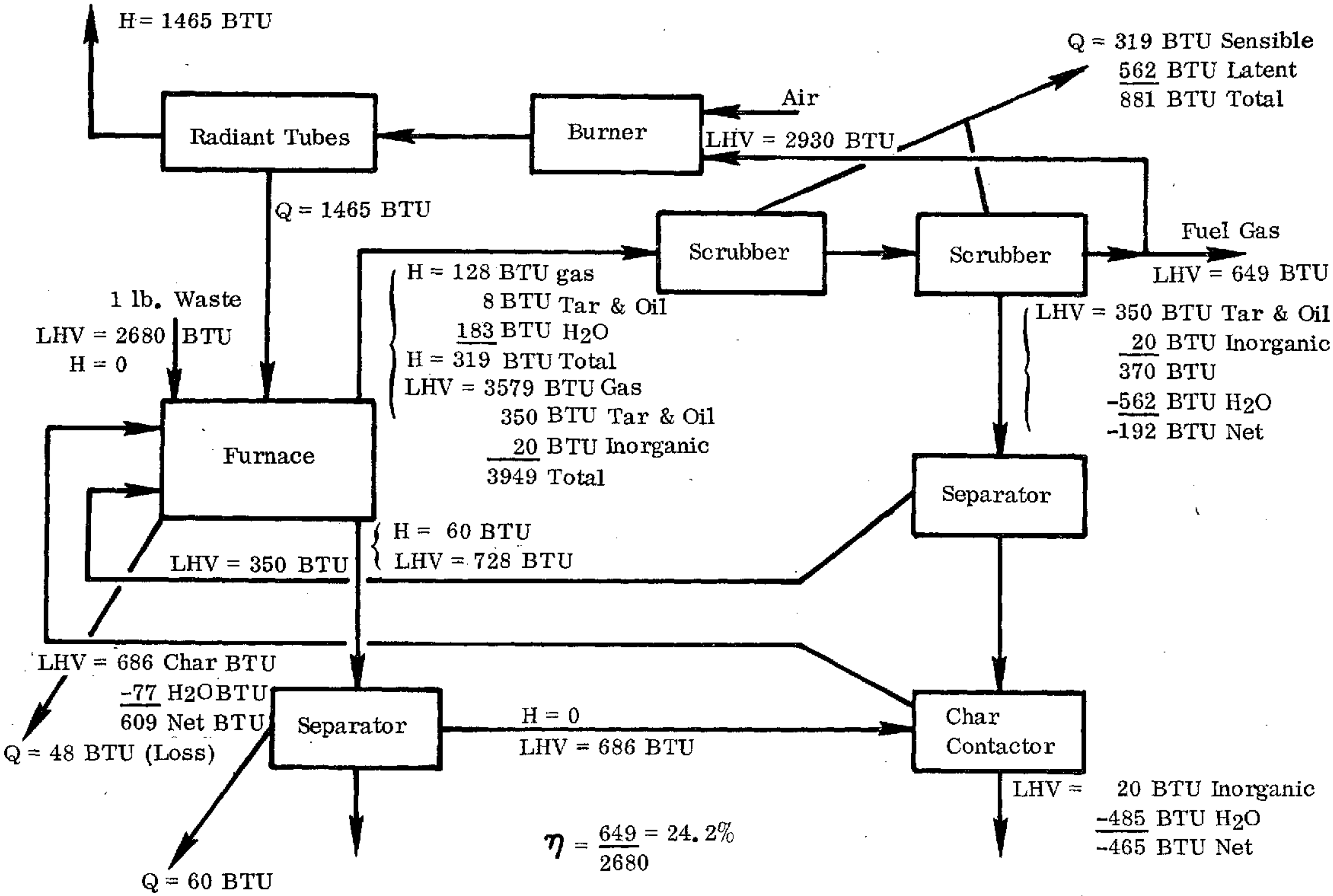
Barber Colman Pyrolysis System Energy Balance (No Power) Case 1

FIGURE 2



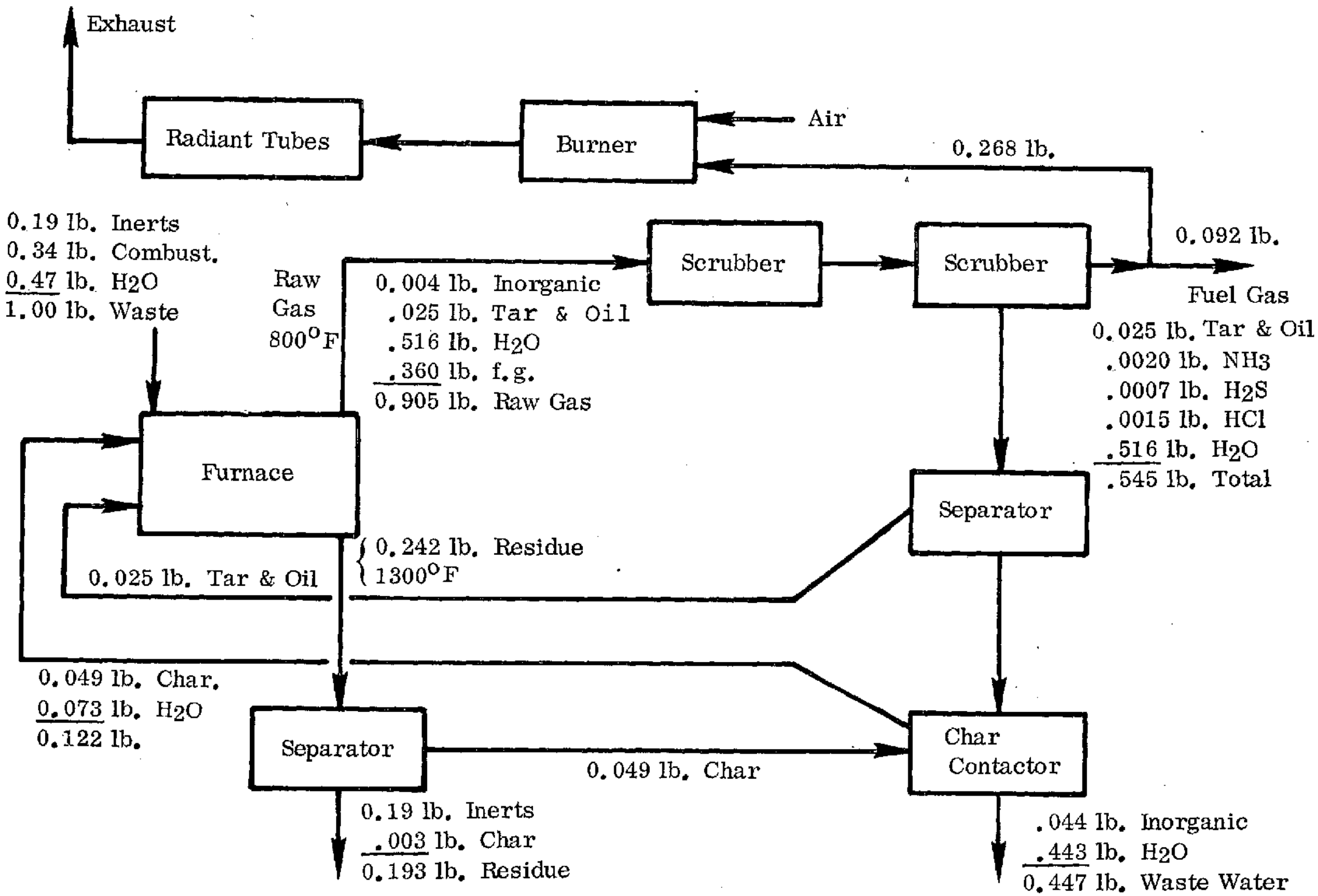
Barber Colman Pyrolysis System Mass Balance Case 2

FIGURE 3



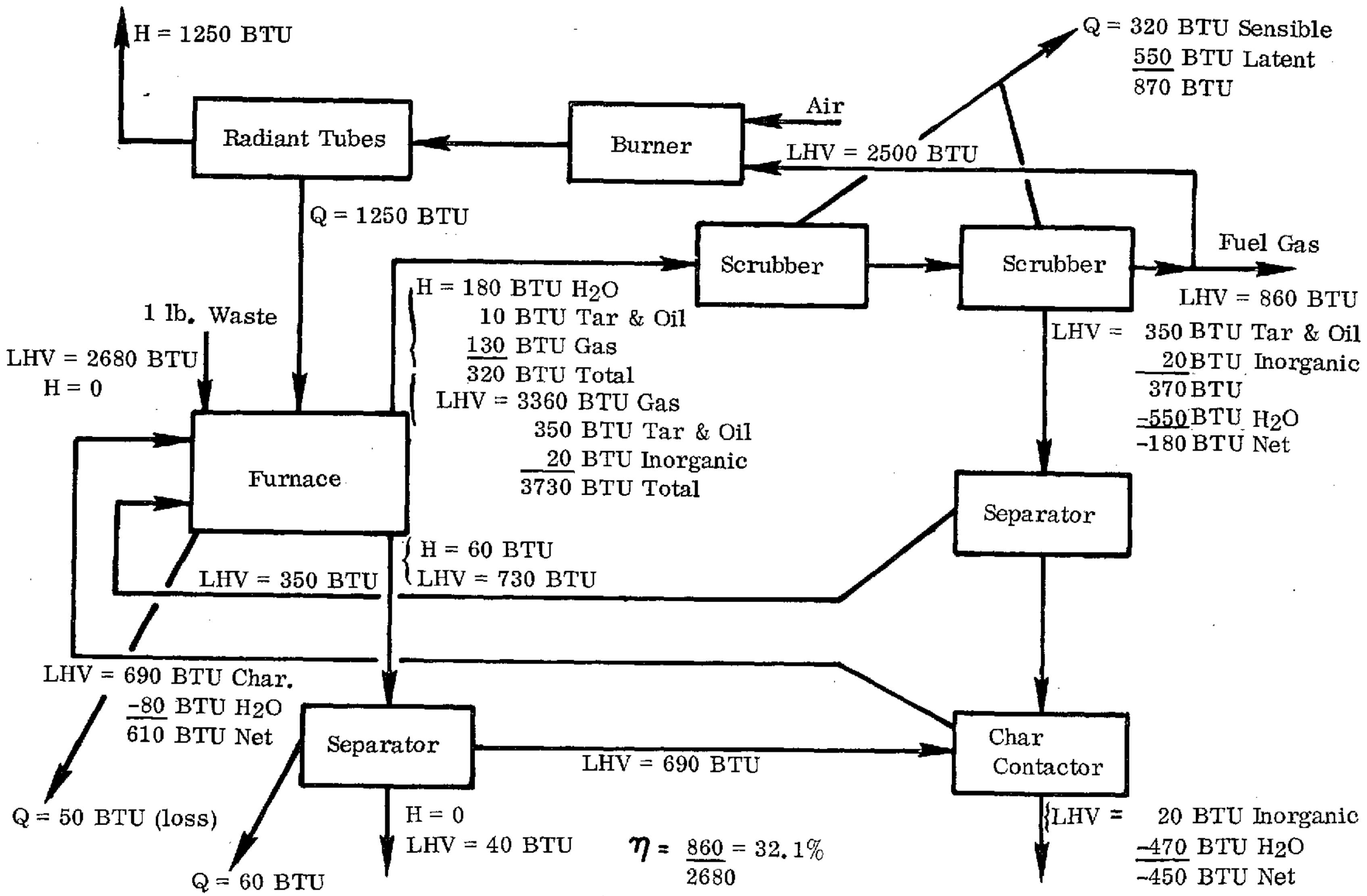
Barber Colman Pyrolysis System Energy Balance Case 2

FIGURE 4



Barber Colman Pyrolysis System Mass Balance Case 3

FIGURE 5



Barber Colman Pyrolysis System Energy Balance (No Power) Case 3

FIGURE 6

TABLE 1 - SUMMARY

Case	1	2	3
Net Fuel Gas LHV	1,235 Btu	649 Btu	860 Btu
Efficiency (Not Considering Electrical Power Consumption)	46%	24%	32%

TABLE 2 - FUEL GAS COMPOSITION

(Case 1, Air Oxidation)

Composition (Mol %)	
N_2	46.2%
H_2	13.4%
CO	15.4%
CH_4	6.1%
C_2H_6	0.5%
C_2H_4	2.2%
C_3H_8	0.5%
CO_2	15.7%
	100.0%

Since Barber-Colman does not wish to operate their system in an air gasification mode, the most optimum steam gasification projections (i.e., Case 3, the Hamilton Standard projection) were used in IUS/Barber-Colman system integration studies. However, it should be borne in mind that this projection assumes that char can be oxidized in the absence of air in a single pass through the furnace. This assumption is not in agreement with the known oxidation kinetics of the steam/char system at the desired furnace temperatures.

The gas composition used in all projections is the one furnished by NASA (see Appendix A-3). This composition at best will be an approximation of the gas that would be produced from the specific IUS waste combined with char recycle. However, there simply is too little information available on the behavior of the Barber-Colman system to allow the development of a complete, internally consistent mass and energy balance on either an experimental or theoretical basis. The gas composition and properties are summarize in Table 3.

TABLE 3 - BARBER-COLMAN FUEL GAS

(Case 3, Steam Oxidation)

Composition (Mol %):

H_2	35.9%
CO	19.2%
CH_4	16.3%
C_2H_6	1.3%
C_2H_4	5.9%
C_3H_8	1.3%
CO_2	20.1%
	100.0%

Properties:

Molecular Weight:	20.1 Lb/Mol
HHV:	494 Btu/Ft^3 Gas
LHV:	449 Btu/Ft^3 Gas
	86 Btu/Ft^3 Stoic. Mix.
	90 Btu/Ft^3 Stoic. Comb. Prod.
Stoichiometric Volume:	4.23 Ft^3 Air/Ft^3 Gas
	5.23 Ft^3 Mix./Ft^3 Gas
	4.97 Ft^3 Comb. Prod./Ft^3 Gas

APPENDIX C4

BARBER-COLMAN PYROLYSIS SYSTEM COSTS

C4

BARBER-COLMAN PYROLYSIS SYSTEM COSTS

An economic analysis of the Barber-Colman pyrolysis system was made at 6, 45 and 250 ton/day sizes based on municipal refuse disposal or utility operation on continuous duty (24 hours/day) for six days per week. Capital outlay for an installed system, annual operation and maintenance, and the dollar value of the net fuel gas produced are shown in Table 1. These estimates are also illustrated in Figures 1 through 3 compared with the URDC system. Detail rationale for these estimates is presented in the following sections.

CAPITAL COSTS

The estimates of capital outlay for the 6, 45 and 250 TPD installed systems were based on estimates of component costs for each system increased by 27 percent (based on estimate for 6 TPD system) for installation, duct, pipe, wire and site preparation and 50 percent for engineering and supplier handling. Table 2 summarizes these results.

Component cost estimates for the three system sizes are shown in Table 3. Table 4 shows the estimates for duct, pipe, wire and installation for the six TPD system.

BARBER-COLMAN PYROLYSIS SYSTEM COST

An estimate of the component costs for the Barber-Colman pyrolysis system has been made for use in the economic study of the two pyrolysis systems. The component costs shown in Table 3 represen

TABLE 1
BARBER-COLMAN UTILITY PYROLYSIS SYSTEM
ECONOMIC EVALUATION

(Thousands of Dollars)

TBD	Capital Outlay	Annual O&M(1)	Annual Net Fuel Produced(2,3)
6	218.3	129.4	7.7
45	583.6	146.8	64.7
250	2,022.8	207.5	362.0

Notes:

(1) Does not include electrical power costs.

(2) Estimated at $1.85/10^6 Btu. (LHV)

(3) Electrical power deducted from gross fuel at 35.1% electrical conversion efficiency based on LHV.

TABLE 2
BARBER-COLMAN PYROLYSIS SYSTEM CAPITAL COSTS

(Thousands of Dollars)

TPD	6	45	250
Component Costs	123.3	329.7	1,142.8
Duct, Pipe, Wire, Etc. (27%)	33.3	89.0	308.6
Engineering and Supplier Handling (50%)	61.7	164.9	571.4
Total Capital Installed System	218.3	583.6	2,022.8

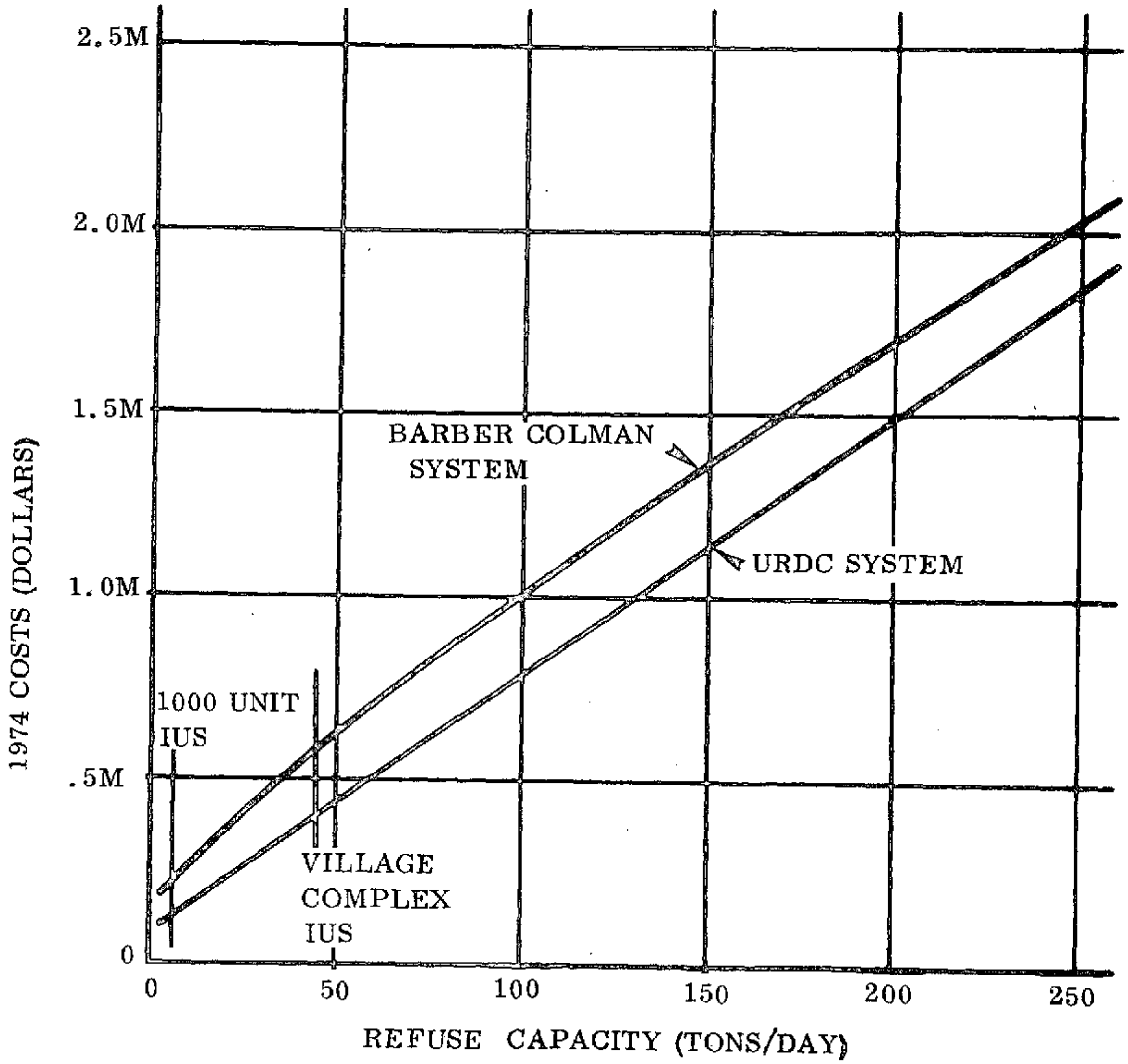


FIGURE 1
PYROLYSIS UTILITY SYSTEMS
CAPITAL COSTS

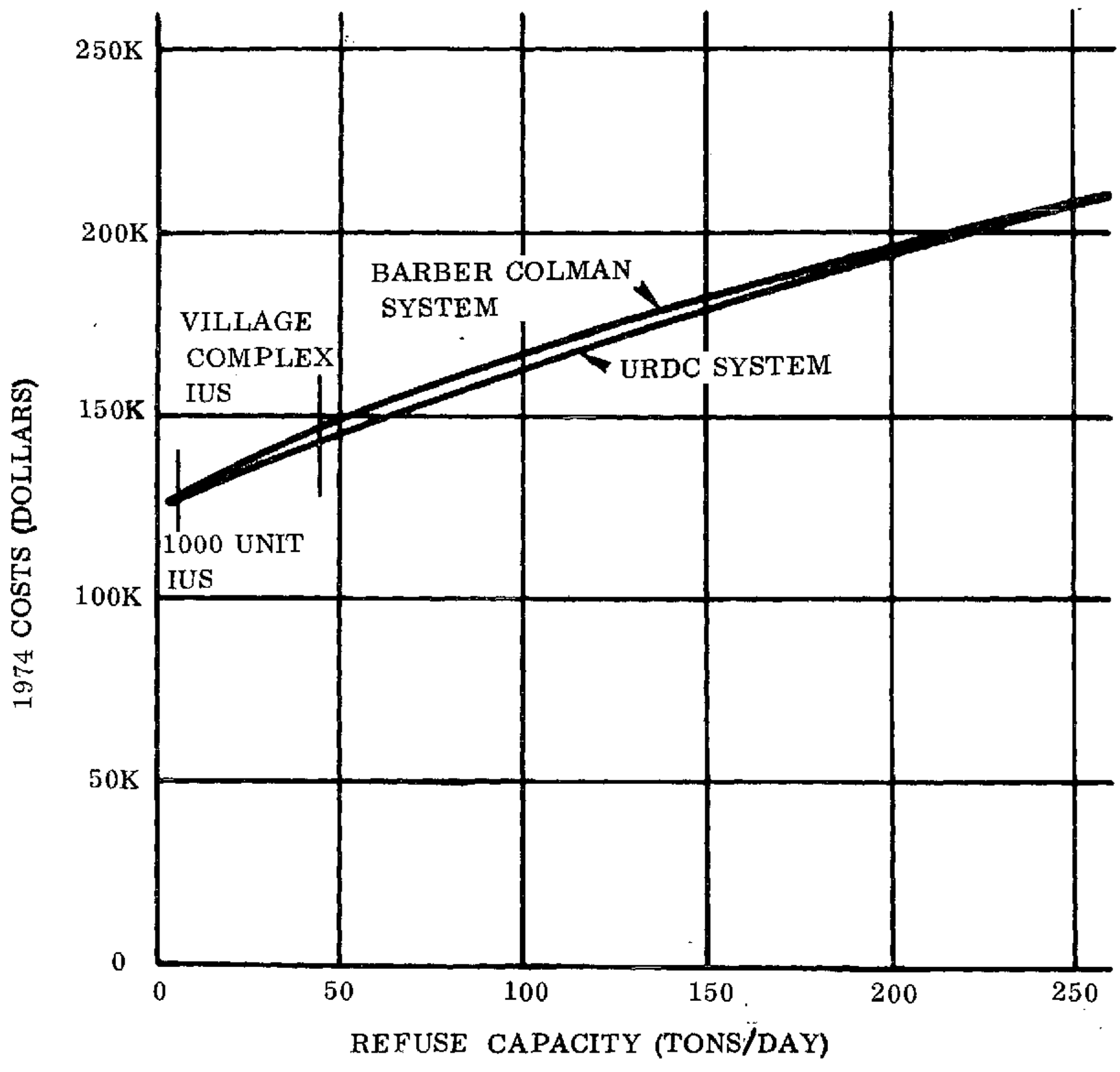
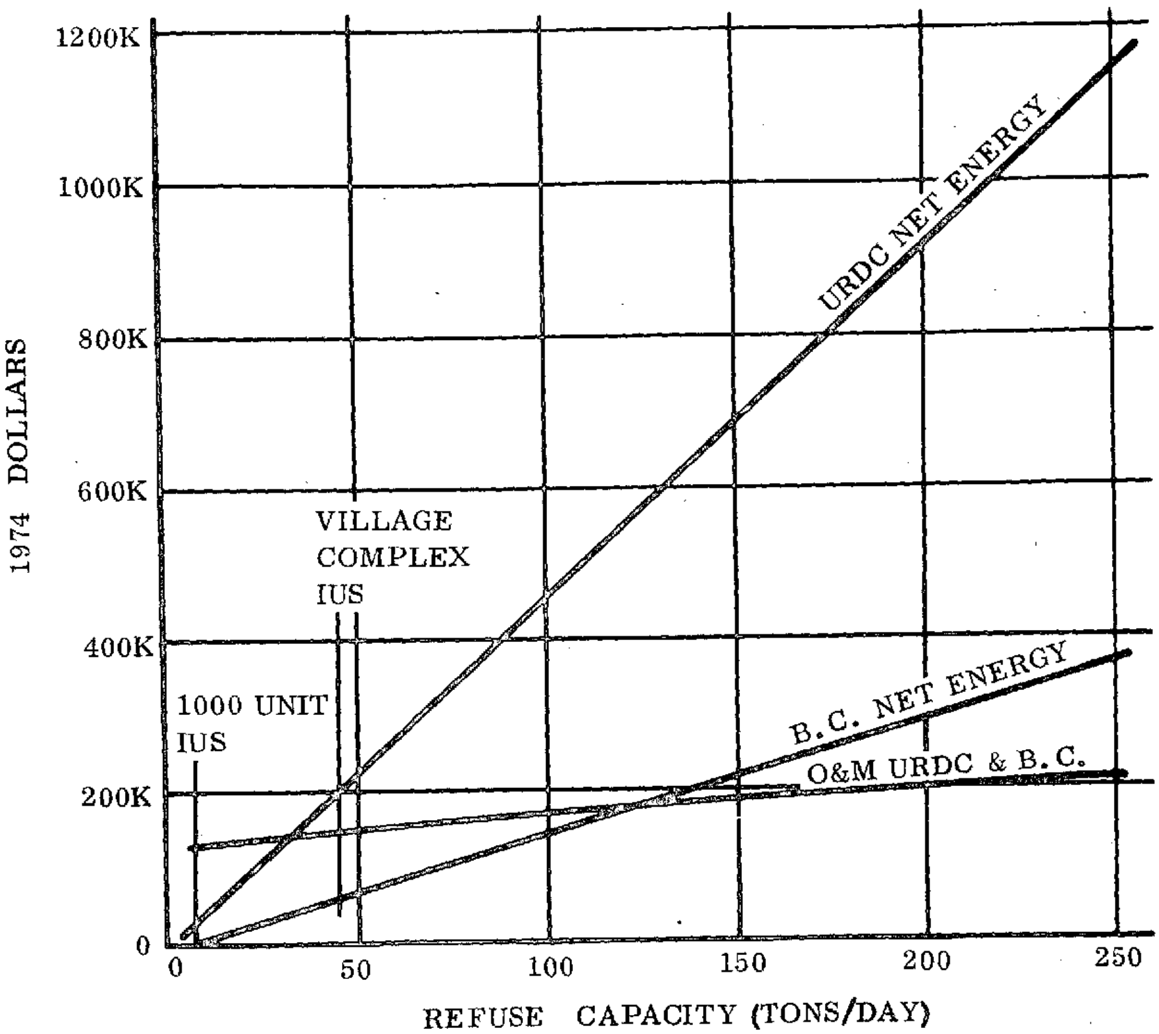


FIGURE 2
ANNUAL OPERATING & MAINTENANCE COSTS
URDC AND BARBER COLMAN
UTILITY PYROLYSIS SYSTEMS



NOTE: NET ENERGY CURVES ARE BASED ON INDICATED REFUSE CAPACITY PLUS SLUDGE CAPACITY. (SLUDGE CAPACITY ≈ .67 X REFUSE)

FIGURE 3
PYROLYSIS UTILITY SYSTEMS
ANNUAL O&M COSTS AND NET ENERGY VALUE
V.S.
REFUSE HANDLING CAPACITY

TABLE 3
BARBER-COLMAN PYROLYSIS SYSTEM COMPONENT COSTS

Item No.	Name	Cost 6 TPD	Cost 45 TPD	Cost 250 TPD	Estimating Technique 6 TPD	Estimating Technique 45 TPD	Estimating Technique 250 TPD
101	Storage Carts 100 Required	45,000	N/A	N/A	Q	--	--
102	Shredder Conveyer						
103	Shredder	21,000	42,000	126,000	Q	Q	Q
104	Storage Conveyer						
105	Storage Silo	28,000	107,000	328,000	RQ	SRQ	SRQ
108	Pyrolysis Reactor	14,500	77,500	430,500	RQ	SRQ	SRQ
111	Back Pressure Control	900	1,000	3,000	Q	E	E
113	Gas Flow Meter	500	500	1,000	E	E	E
114	Excess Gas Burner	2,100	4,500	9,100	Q	E	E
116	Hot Char Conveyer	2,000	2,500	8,000	E	E	E
130	Wash Level Control	3,000	4,000	8,000	RQ	E	E
131	Reactor Air Blower	700	3,000	6,100	Q	RQ	RQ
132	Reactor Air Burner	1,000	5,500	8,800	Q	E	E
133	Reactor Control	3,200	3,500	10,000	DE	E	E
138	Oil Skimmer	500	700	2,000	E	E	E

TABLE 3
(Continued)

Item No.	Name	Cost 6 TPD	Cost 45 TPD	Cost 250 TPD	Estimating Technique 6 TPD	Estimating Technique 45 TPD	Estimating Technique 250 TPD
140	Hot Gas Blower	800	3,500	7,000	Q	Q	Q
141 142	Reactor Feed Conveyer Compactor Screw Conveyer	10,000	13,000	24,000	Q	Q	Q
143	Fume Vent Blower	500	700	1,000	Q	RQ	RQ
144	Intake Filter	200	300	500	E	E	E
145	Flue Box After Burner	6,000	10,000	40,000	RQ	E	E
146	Lead Circulation Pump	300	400	700	Q	E	E
147	Wash Water Pump	800	900	6,700	Q	Q	Q
148	Residue Conveyer	3,000	4,300	8,000	RQ	RQ	RQ
149	Char Flotation Tank	2,000	4,000	10,000	E	E	E
150	Oil and Tar Pump	200	200	1,000	Q	Q	E
151	Char Dewatering Separator	1,000	2,000	5,000	E	E	E
152	After Burner Preheat	1,000	1,000	3,000	Q	Q	E
153	Char Quench Conveyer	3,000	4,300	8,000	RQ	RQ	RQ

TABLE 3
(Continued)

Item No.	Name	Cost 6 TPD	Cost 45 TPD	Cost 250 TPD	Estimating Technique 6 TPD	Estimating Technique 45 TPD	Estimating Technique 250 TPD
154	Gas Scrubber	8,000	13,000	38,000	Q	Q	Q
155	Separator Demister						
156	Wash Drain Pump	800	900	6,700	RQ	RQ	RQ
157	Wash Water Cooler	4,500	14,300	28,000	Q	RQ	RQ
158	Char Conveyer	3,000	4,300	8,000	RQ	RQ	RQ
159	Char Slurry Pump	800	900	6,700	RQ	RQ	RQ
	Total (Excluding Carts)	123,300	329,700	1,142,800			

LEGEND: Q = Quote - Letter or Temperature Quote

RQ = Ratioed Quote - Q Multiplied by Some Known or Calculated Ratio

SRQ = Scaled RQ - RQ Scaled Up for TPD Size

E = Estimate - Best Estimate (Based on 6 TPD Unit When Possible)

DE = Detailed Estimate - Based on Estimate of Many Small Items

TABLE 4
INSTALLED COSTS
SIX TPD BARBER-COLMAN PYROLYSIS SYSTEM

Component	Component Cost	Installation	Installed Cost	Maint.
Shredder W/2 Conveyers	$21,000	$4,000	$25,000	$2,000
Storage Silo	28,000	3,000	31,000	840
Pyrolysis Reactor	14,500	1,900	16,400	1,111
Back Pressure Control	900	800	1,700	27
Gas Meter	500	300	800	15
Excess Gas Burner	2,100	700	2,800	63
Hot Char Conveyer	2,000	500	2,500	60
Wash Level Control	3,000	300	3,300	90
Reactor Air Blower	700	400	1,100	21
Reactor Air Burner	1,000	400	1,400	30
Reactor Control	3,200	1,000	4,200	96
Oil Skimmer	500	200	700	15
Hot Gas Blower	800	600	1,400	24
Reactor/Compactor Conveyers	10,000	2,000	12,000	300

TABLE 4
(Continued)

Component	Component Cost	Installation	Installed Cost	Maint.
Fume Vent Blower	$ 500	$ 400	$ 900	15
Intake Filter	200	50	250	6
Flue Box After Burner	6,000	400	6,400	180
Lead Circulation Pump	300	500	800	9
Wash Water Pump	800	200	1,000	24
Residue Conveyer	3,000	400	3,400	90
Char Flotation Tank	2,000	500	2,500	60
Oil and Tar Pump	200	300	500	9
Char Dewatering Separator	1,000	400	1,400	30
After Burner Preheat	1,000	300	1,300	30
Char Quench Conveyer	3,000	800	3,800	90
Gas Scrubber & Separator Demister	8,000	1,500	9,500	240
Wash Drain Pump	800	400	1,200	24
Wash Water Cooler	4,500	400	4,900	135

TABLE 4
(Continued)

Component	Component Cost	Installation	Installed Cost	Maint.
Char Conveyer	$ 3,000	$ 750	$ 3,750	$ 90
Char Slurry Pump	800	500	1,300	24
Miscellaneous Installation (25%)	--	6,000	--	--
Subtotal Component Cost	$123,300	--	--	--
Duct and Pipe	2,800	--	2,800	84
Wire	1,100	--	1,100	33
	$127,200	$29,900	$157,100	$5,865
Engineering & Handling (50% of Comp. Cost)			61,650	
Installed System			$218,750	

$$\text{Factor} = \frac{157.1 - 123.3}{123.3} = 27.4\%$$

a mixture of firm letter quotes from suppliers, telephone quotes, catalog prices, and estimates based on comparisons with know prices. All values represent the FOB cost at point of manufacture. The Table includes a code to indicate the estimating technique used for each component. The estimating technique code is as follows:

Q - This indicates a firm budgetary quote from the manufacture of the equipment either by letter or telephone; a direct catalog item price; or a vendor's budgetary quote on a non-standard size unit.

RQ - This is a ratioed quote and is used when a firm quote (Q) is available for a similar item, and a known size or capacity ratio exists. For example, the 6 TPD Barber-Colman reactor (item 108) is a known ratio smaller than the 6 TPD URDC reactor (item 204) for which an accurate modified quote exists, so the cost has been ratioed down accordingly. In the case of pumps and blowers, one pump supplier and one blower supplier offered firm quotes for all three sizes 6, 45 and 250 TPD. The ratio of these numbers was applied to other size pump or blower quotes for 6 TPD units to obtain the corresponding 45 and 250 TPD unit costs.

SRQ - This is used to scale up an RQ for size in the same way as an SMQ scales an MQ.

E - Represents an estimate without specific vendor quote data as back up. In most cases where E is used, a Q or an RQ exists for the 6 TPD size unit but not for larger sizes, and the estimate for these larger sizes was made based on the expected difference between a 6 TPD unit and that required for a 45 or 250 TPD unit.

DE - Represents the detailed estimate made for the control systems and includes catalog prices on components and cabinets expected to be required for the control function.

Storage carts (101) are not included in the totals since they apply only to the 6 TPD IUS plant, and their cost is part of the IUS cost.

The TPD notation applys only to the tons of trash handled by each system and does not include the sewage sludge capabilities of the systems. For example, the equipment specified for the 6 TPD unit has additional capacity to handle 4 TPD of sewage sludge for a total of 10 TPD.

The estimates of installation costs shown in Table 4 for each component were made by an engineer experienced in the construction and facilities field. Site preparation is included in these estimates.

OPERATION AND MAINTENANCE

The estimated operation and maintenance expenses are summarized in Table 5. The major portion of these costs are operator labor

TABLE 5
BARBER-COLMAN PYROLYSIS SYSTEM
ANNUAL OPERATING AND MAINTENANCE COSTS

TPD	6	45	250
Component Costs	$123.3	$329.7	$1,142.8
Labor	$123.0	$131.0	$174.4
Misc. Op. Expense (.5% Comp.)	.6	1.6	5.7
Total Operating Expense	$123.6	$132.6	$180.1
Maintenance %	4.7	4.3	2.4
Maintenance Expense	5.8	14.2	27.4
	$129.4	$146.8	$207.5

charges shown in Table 6 for the 6 and 250 TPD system. The labor costs for the 45 TPD system was estimated on a straight line relationship between the 6 and 250 TPD systems. It was assumed that two operators would be a minimum required for any pyrolysis system for safety reasons. This was used for the 6 TPD system, and one additional operator was added for the 250 TPD system.

An estimate of cost for three shift coverage for seven days per week is four men for each position in order to cover vacations, sick time, weekends, etc. Accordingly, the salaries for one shift coverage were factored by 4 x 6/7 for six day operation. An engineer spending 10% of his time is included in the expense. An additional 1/2% of the component costs was included for miscellaneous operating expenses.

Maintenance for the 6 TPD system was estimated by the economic ground rules prepared earlier in the study. This fraction of the total component costs at the 6 TPD system size was assumed to decrease linearly to one-half the value for the 250 TPD system

NET FUEL GAS PRODUCED

The net fuel gas produced was calculated based on the performance estimate of 860 Btu/lb LHV of waste input to the system with the electrical energy consumption deducted based on a generator with electrical conversion efficiency of 35.1% on the LHV. The fuel

TABLE 6
PYROLYSIS SYSTEMS LABOR EXPENSES

6 TPD System

1 Skilled Operator	$ 20,000
1 Semi-Skilled Operator	15,000
	$ 35,000
3 Shift Coverage, 6 Days/Week	x 4x6/7
	$120,000
1 Engineer, 10% Time @ $30K/Year	3,000
	$123,000

250 TPD System

1 Skilled Operator	$ 20,000
2 Semi-Skilled Operators	30,000
	$ 50,000
3 Shifts, 6 Day/Week	x 4x6/7
	$171,400
1 Engineer, 10% Time @ $30K/Year	3,000
	$174,400

value was taken at $1.85/10^6$ Btu per the study ground rules. Start up fuel requirements were ignored because they would have a maximum effect of 4% decrease in the net energy produced. Table 7 shows a summary of the net energy for the three system sizes considered.

TABLE 7

ECONOMIC VALUE OF NET ENERGY
PRODUCED BY THE BARBER-COLMAN PYROLYSIS SYSTEM

System Capacity	(TPD)	6	45	250
Average Electrical Power	(KW)	21.21	166.7	902.0
Annual Electrical Energy	(10^6 BTU)	697.6	4,274	23,126
Fuel Required @ 35.1% Eff.	(10^6 BTU)	1,987	12,100	65,888
*Fuel Produced	(10^6 BTU)	6,278	47,085	261,583
Net Fuel	(10^6 BTU)	4,291	34,985	195,695
Net Value of Energy @ $1.85/$10^6$ BTU		$7,938	$64,722	$362,036

*Based on 12 TPD refuse plus 8 TPD sewage sludge

APPENDIX C5

POWER SUMMARY FOR

BARBER-COLMAN PYROLYSIS SYSTEM

C5

POWER SUMMARY FOR BARBER-COLMAN PYROLYSIS SYSTEM

A power summary for the Barber-Colman Pyrolysis System has been prepared showing the peak power for each major electrical consuming item. A load factor is applied to indicate the amount of time the component is operating for each day of system operation, resulting in an average daily power consumption rate. All sizing is based on 24 hour per day, 6 day per week operation at a plant receiving six tons of trash and four tons of sewage sludge seven days per week.

BARBER-COLMAN POWER SUMMARY

Item No.	Name	Peak Power (KW)	Duty Cycle	Average Power (KW)
102	Shredder Conveyer	2.0	.0729	.12
103	Shredder	75.0	.0729	3.15
104	Storage Conveyer	2.0	.0729	.12
111	Back Pressure Control	.2	1	.2
114	Excess Gas Burner	2.53	0	0
116	Hot Char Conveyer	.5	1	.5
130	Wash Level Control	.1	1	.1
131	Reactor Air Blower	3.26	1	3.26
133	Reactor Control	.5	1	.5
140	Hot Gas Blower	2.39	1	2.39
141	Reactor Feed Conveyer	3.0	1	3.0
142	Compactor Screw Conveyer	2.0	1	2.0
143	Fume Vent Blower	.43	1	.43
146	Lead Circulation Pump	2.0	1	2.0
147	Wash Water Pump	4.56	1	4.56
148	Residue Conveyer	1.0	1	1.0
149	Char Flotation Tank	.33	1	.33
150	Oil and Tar Pump	.05	1	.05
152	After Burner Preheat	.13	0	0
153	Char Quench Conveyer	1.0	1	1.0
156	Wash Drain Pump	.5	1	.5
158	Char Conveyer	1.0	1	1.0
159	Char Slurry Pump	1.0	1	1.0
		107.48		27.21

APPENDIX D1

INTEGRATED UTILITY SYSTEM WASTE FEED DATA

D1

IUS WASTE FEED DATA

The IUS waste data used in the Pyrolysis Evaluation Study is given in Table 1. Quantities of refuse and sludge were taken from the MIUS system study (1) and doubled for the basic thousand unit IUS. Sludge solids content, as well as refuse and sludge heating values, also were taken from this study.

The refuse was assumed to contain 25% water and 25% inerts. This leaves 50% combustible which is typical of average municipal refuse. However, the water is a little lower and the inerts are a little higher than the average. The inerts were increased for the IUS application since this waste is essentially residential which generally has a much higher inert content than industrial or commercial refuse. (Residential refuse easily can run as high as 30% inert.) See Ref 2 for a discussion of this point. The lower than average water content assumed would be expected because of the weather sheltered collection system used by the IUS, and the relative lack of garbage and yard wastes.

The sludge solids were assumed to be 50% inert (ash) which would imply a HHV of 10,000 Btu/lb burnables. This combination is typical.

The detailed properties of the waste feed then were calculated on a combined basis (i.e. refuse + sludge = waste). The composition of the combustible portion was assumed to be the same as for the combustible portion of refuse. This assumption was

necessary since very little elemental composition data is available for sewage sludge. In any case, since the sludge only represents 12% of the burnables, the potential error is small.

The starting point for the composition was taken from Kaiser (3). This composition is quite similar to average refuse as indicated by an extensive study by Niessen (4) but is less likely to lead to internal inconsistencies since it represents an actual set of measurements.

The fixed carbon content was taken directly from Kaiser. However, several modifications were made to the elemental composition. The Kaiser analysis did not include any chlorine and therefore the value was assumed based on measurements taken in conjunction with the St. Louis/Union Electric project (5). A further correction was necessary because of the somewhat higher than normal heating value. That is, the HHV of the waste feed is 10,000 Btu/lb of burnables while the corresponding value for the Kaiser refuse is approximately 9,000 Btu/lb. Therefore to insure that reasonable results would be obtained in the internal heat and mass balance calculations, the oxygen content of the waste feed had to be reduced from that of typical refuse. This was done via the Dulong equation:

$$HHV = 14,600\ C + (H_2 - O_2/8) + 4050\ S$$

This equation was derived for coal and does not give a very accurate representation of the heating value of refuse. However, it was felt to be adequate to predict the effect of changing composition on heating value for small changes.

The correction procedure was as follows. The composition was taken as Kaiser's and a heating value of 9,000 BTU/lb was assumed. The IUS waste feed heating value was assumed to be 10,000 BTU/lb. The increased heating value was assumed to be due to a lowered oxygen content and correspondingly increased hydrogen and carbon contents. The hydrogen/carbon ratio was assumed to stay constant. The Dulong equation then could be used to predict the changes in carbon, oxygen and hydrogen composition necessary to produce the increased heating value.

Relevant collection system characteristics were also taken from the MIUS report with the appropriate quantities doubled to reflect the increase to 1,000 apartment units.

REFERENCES

1. Preliminary Design Study of a Baseline MIUS System, Urban Systems Project Office, NASA, JSC, Houston, Texas, April, 1974

2. Eggen, A.C.W., and Kraatz, R., "Relative Value of Fuels Derived from Solid Wastes", Proceedings 1974 National Incinerator Conference, ASME, New York, 1974.

3. Kaiser, E.R., and Zeit, D.C., and McCaffery, "Municipal Incinerator Refuse and Residue", Proceedings 1968 National Incinerator Conference, ASME, New York, 1968.

4. Niessen, W.R., and Chansky, S.H., "The Nature of Refuse", Proceedings 1970 National Incinerator Conference, ASME, New York, 1970.

5. Doty, W.H., et al., "The Analysis of Refuse", Proceedings Solid Waste Disposal Seminar, Union Electric Co., St. Louis, 1972.

TABLE 1

IUS WASTE FEED

Quantities - 1000 Unit IUS

Refuse - 12,000 lb/day

Sludge - 8,000 lb/day

Collection and Storage:

28 carts/day to disposal

96 carts in system (total) - approximately 3 day storage capacity

37.5 ft^3/cart

10 lb/ft^3 refuse avg. (4-11 lb/ft^3 typical range, uncompacted)

Composition

Refuse	Sludge	Average Waste
25% H_2O	80% H_2O	47% H_2O
25% Inert	10% Inert	19% Inert
50% Burnable	10% Burnable	34% Burnable
5000 Btu/lb	5000 Btu/lb Solids	3400 Btu/lb (HHV)

Average Waste, Burnable Portion

87% Volatile

13% Fixed Carbon

10,000 Btu/lb (HHV)

Average Burnable Composition by Weight

53.0%	Carbon
7.0%	Hydrogen
38.4%	Oxygen
1.0%	Nitrogen
0.2%	Sulfur
0.4%	Chlorine
100.0%	

APPENDIX D2

INTEGRATED UTILITY SYSTEM FLOW CHART MODELS

D2

IUS FLOW CHART MODELS

The IUS energy balance charts were generated based on the following system and subsystem ground rules and models.

IUS Loads

	Spring	Summer	Fall	Winter	Annual
Electrical (10^3 KW-Hrs)*	2,631	2,631	2,603	2.574	10,439
Air Conditioning (10^3 Ton-Hrs)	289	1,046	347	8	1,690
Space Heating (10^6 Btu)	511	0	339	4,282	5,132
Dom. Water Heat (10^6 Btu)	5,789	5,789	5.726	5,663	22,967

*Domestic plus aux. except for compression chilling, solid waste disposal and electric steam generator loads.

Domestic Water Heating High Grade to Low Grade Splits (10^6 Btu)

With Diesel Generators - Splits are taken from the MIUS Design Study Report.

	Spring	Summer	Fall	Winter	Annual
High Grade Heat	1,868	1,611	1,838	3,089	8,406
Low Grade Heat	3,921	4,178	3,888	2,574	14,561

With Fuel Cells - A maximum of 25% of low grade heat is utilized for heating domestic hot water; remaining from high grade heat.

Space Heating
High Grade to Low Grade Splits

With Diesel Generators - Splits are taken from the MIUS Design Study Report.

	Spring	Summer	Fall	Winter	Annual
High Grade Heat	165	0	109	2,323	2,597
Low Grade Heat	346	0	230	1,963	2,539

With Fuel Cells - All space heating is done with high grade heat.

Steam Utilization

It was assumed, per agreement with the NASA, that 100% of the high grade heat could be used in domestic space and water heating and the absorption chillers prior to starting the compression chillers.

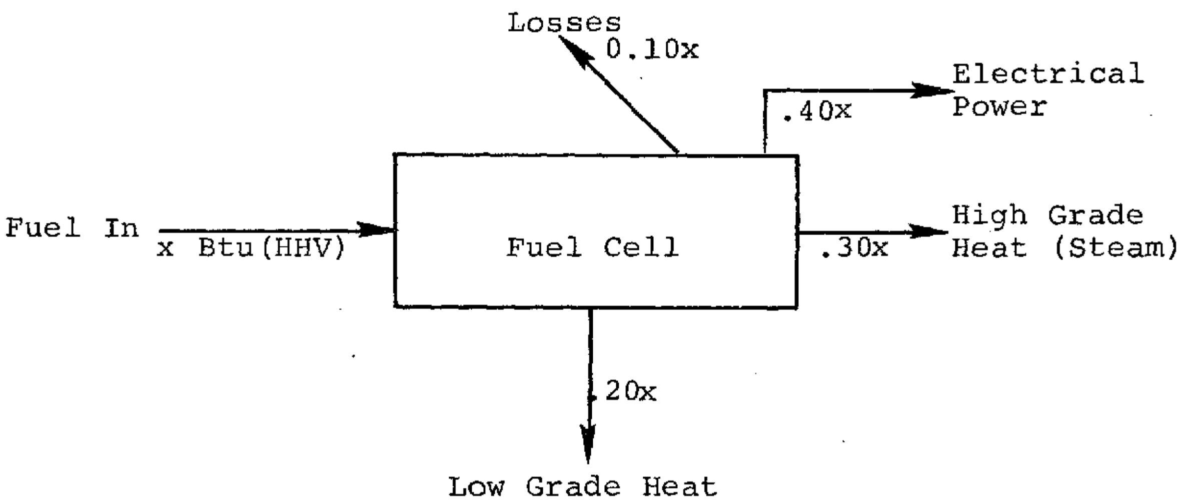
Chillers - Coefficient of Performance

Absorption - 0.67

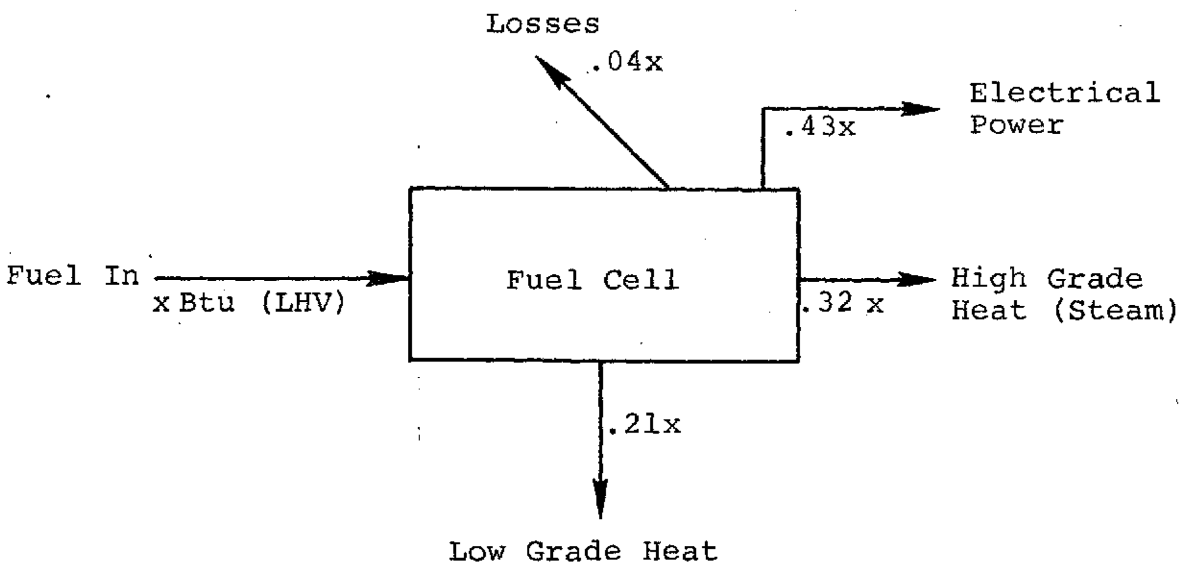
Compression - 4.00

Fuel Cells

Performance based on higher heating value of fuel.

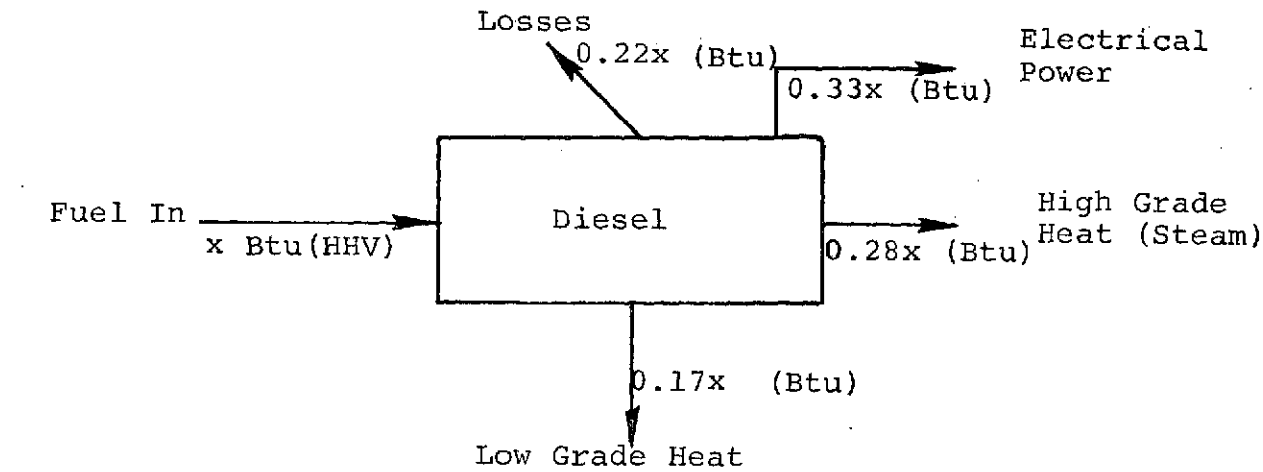


Performance based on lower heating value of fuel.

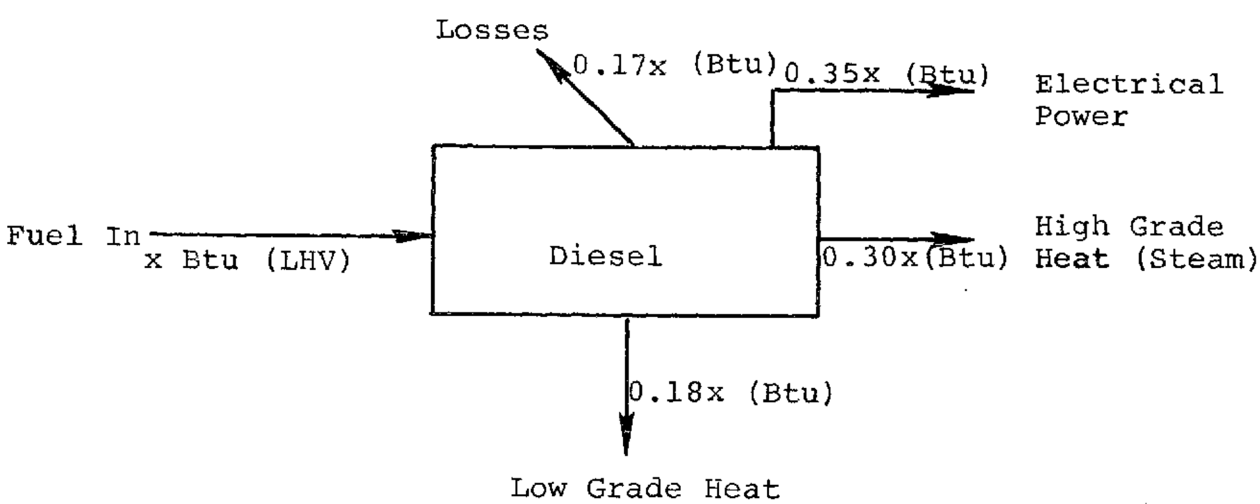


Diesel Generators

Based on higher heating value of fuel.



Based on lower heating value of fuel.



Fuel

Although fuels are normally purchased on an HHV basis, most fuel consuming devices can only utilize the LHV portion. Therefore, if changing fuels does not change the basic efficiency of a given device, one Btu LHV of fuel A is fully equivalent to one Btu LHV of fuel B. This means that 1 Btu of HHV in fuel A is not equal to 1 Btu of HHV in fuel B unless A and B both have the same mass of hydrogen per Btu HHV. For conventional fuels the difference between HHV and LHV can range from the order of 2% for a blast furnace gas -o 10% for natural gas. Raw fuel gas from a fixed bed gasifier can have a considerably greater difference. As a result substitution calculations must be done correctly or rather significant errors can result. In order to minimize the possibility of erroneous calculations the following procedures were used:

1. The baseline IUS energy balance were converted to an LHV basis.

   This required:

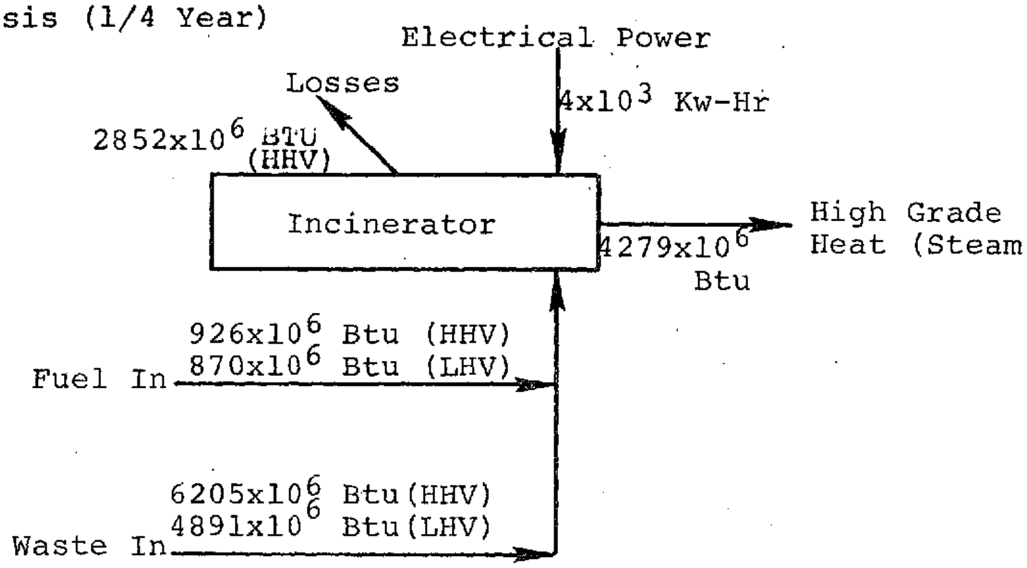
   a. multiplying input fuel HHV's by 0.94 (assumes typical No. 2 diesel oil)

   b. reducing the flue gas losses by an amount equal to the reduction in fuel HHV.

Pyrolysis fuel is substituted for primary fuel on a Btu for Btu basis.

Incinerator

Seasonal Basis (1/4 Year)



Electrical load based on an estimated 3.98 KW, 12/hrs/day, 7 days/week. Total energy/season = 4 KW-hrs.

Fuel required = 15% of wasted based on HHV.

High grade heat recovery = 60% of total heat input (trash + fuel) based on HHV.

IUS Solid Wastes

Trash	12,000	Lb/Day
Sludge	8,000	Lb/Day
HHV	3,400	Btu/Lb
LHV	2,680	Btu/Lb

20,000 Lb/Day X 2,680 Btu/Lb X 365 Day/Yr X .25 Yr/Season =

$4,891 \times 10^6$ Btu/Season

20,000 Lb/Day X 3,400 Btu/LB X 365 Day/Yr X .25 Yr/Season =

$6{,}205 \times 10^6$ Btu/Season

<u>Electrical Steam Generator</u>

Efficiency 100%

<u>Cooling Tower Makeup Water</u>

1,043 Btu/Lb of Makeup Water

APPENDIX D3

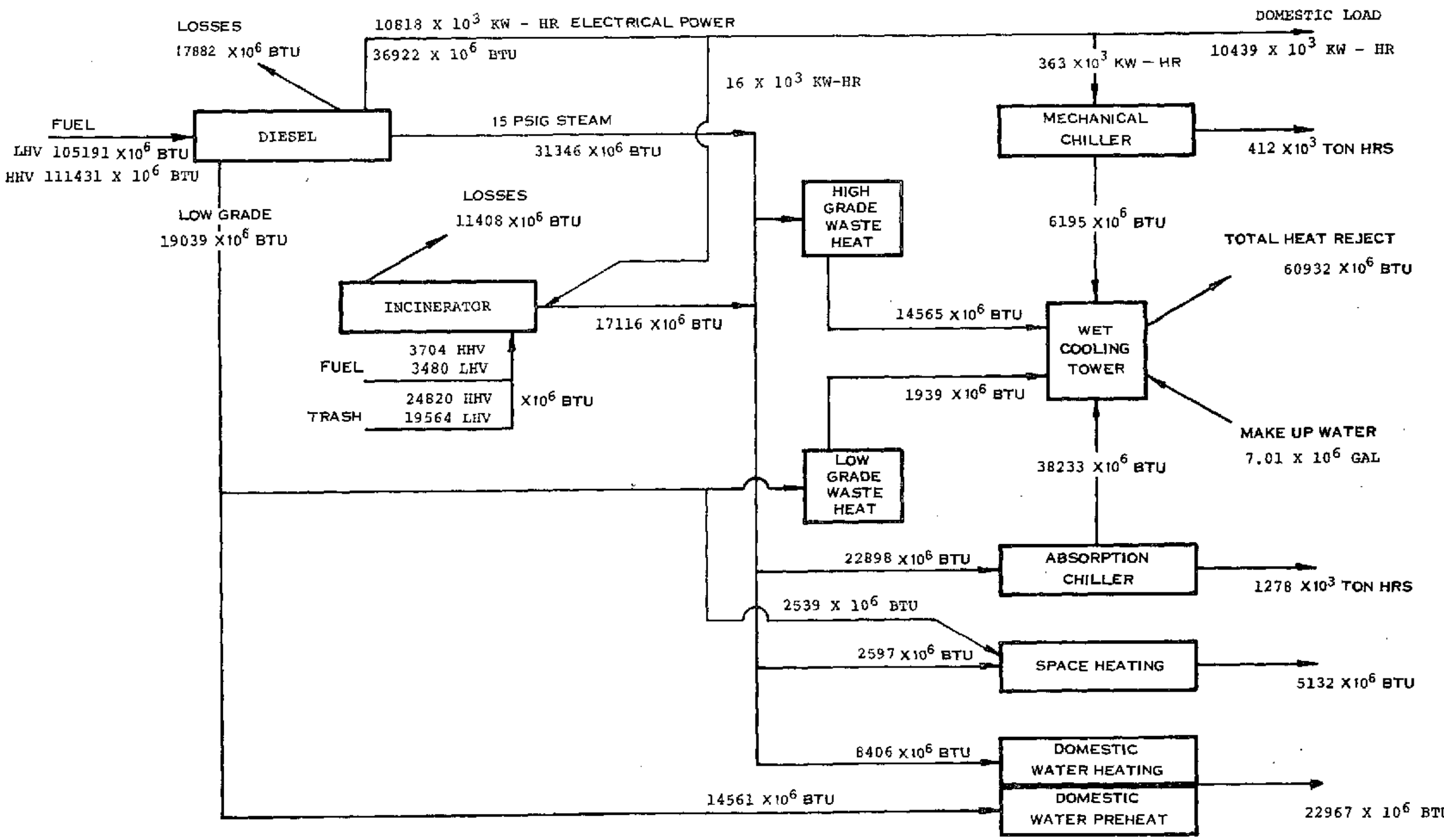
BASELINE INTEGRATED UTILITY SYSTEM

PERFORMANCE FLOW CHARTS

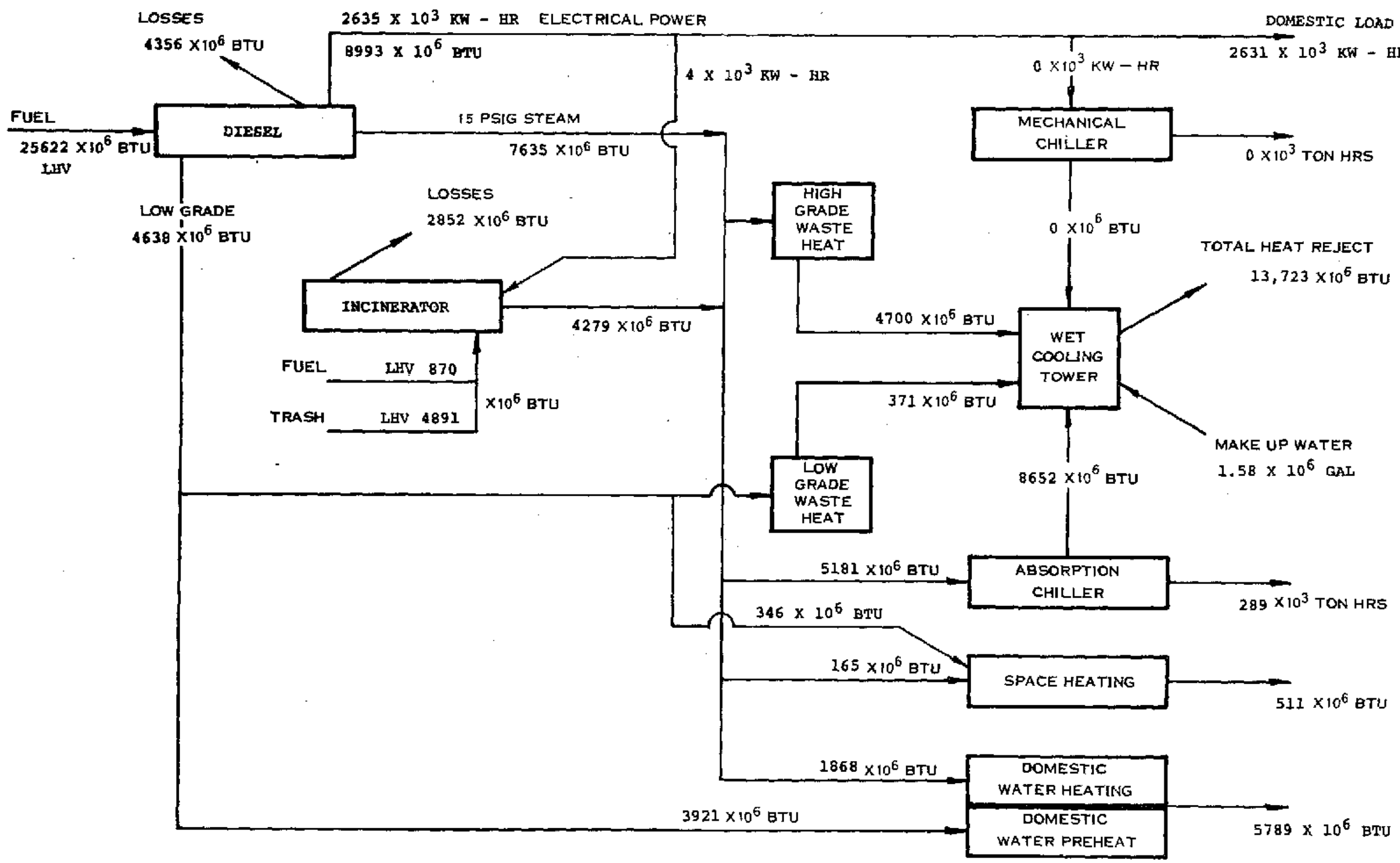
D3

BASELINE IUS - PERFORMANCE FLOW CHARTS

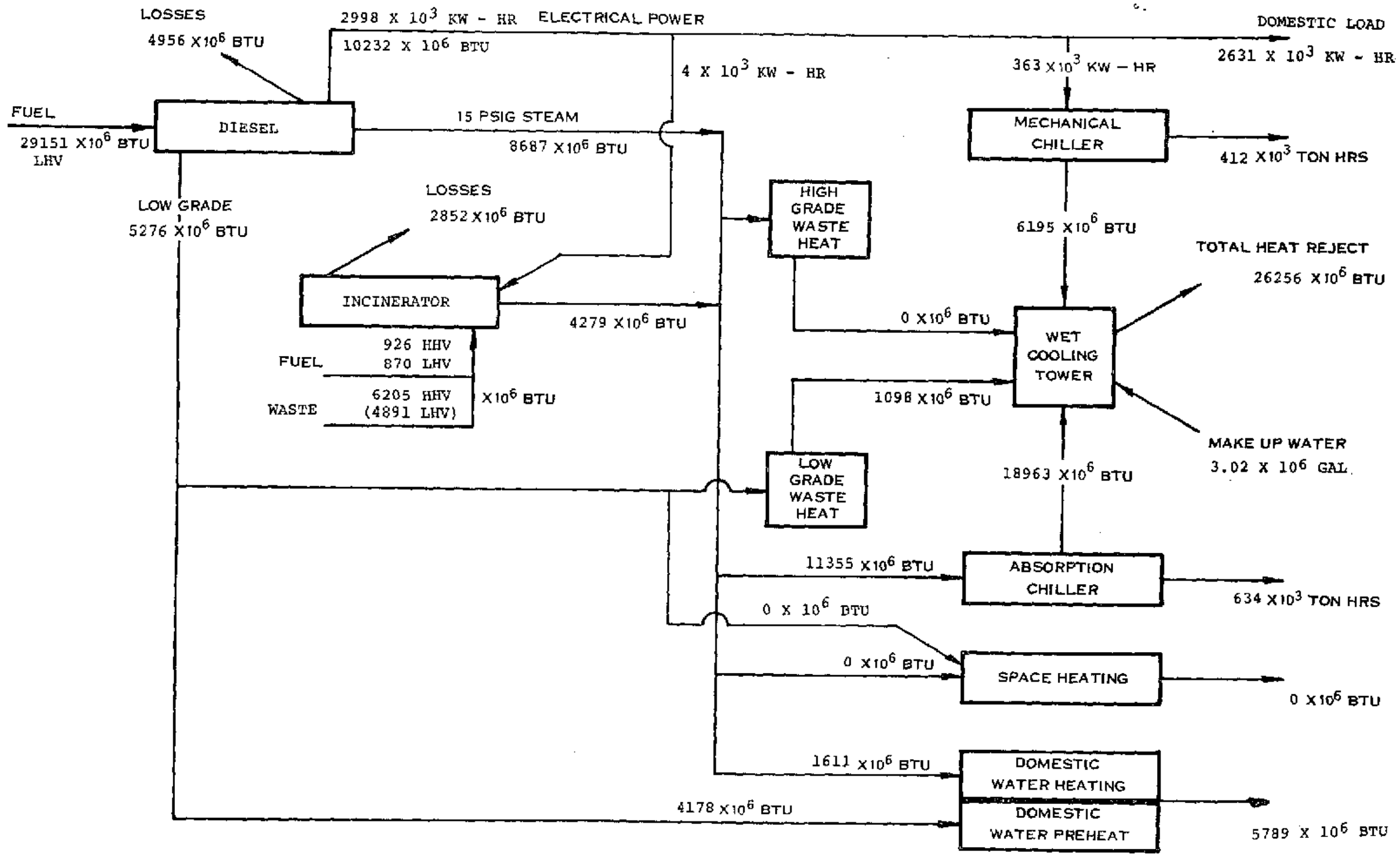
The flow charts which follow present the energy utilization analysis of the 1000 Unit Apartment Complex IUS with an incineration solid waste management system. Another baseline is presented where there is no consideration of solid waste disposal. However, the waste collection cart system is still provided. Fuel cells and diesels are considered for electrical power generation, and the analyses were performed on a seasonal basis with an annual summary made from the seasonal charts.



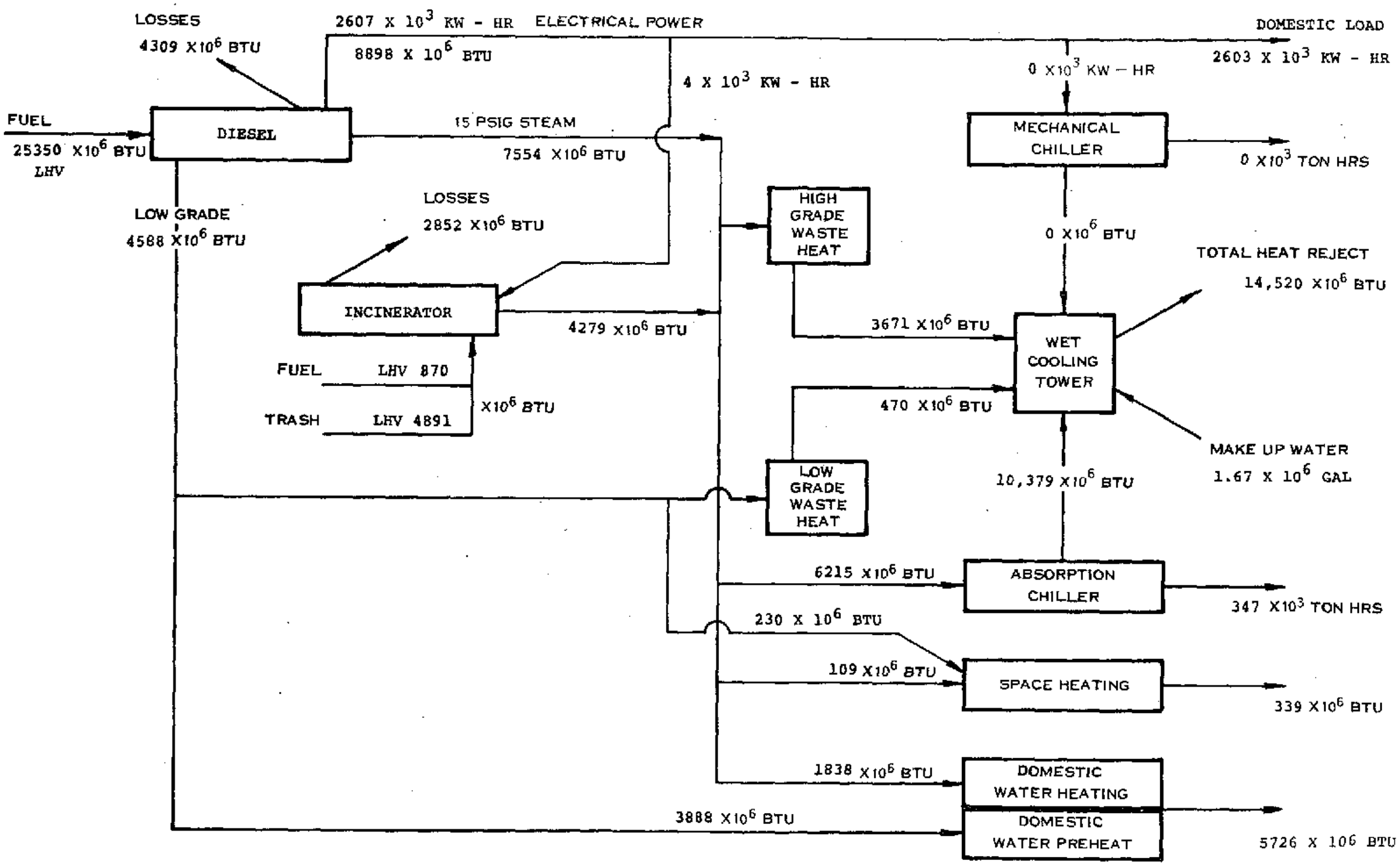
IUS BASELINE - DIESEL - ANNUAL
WITH INCINERATION



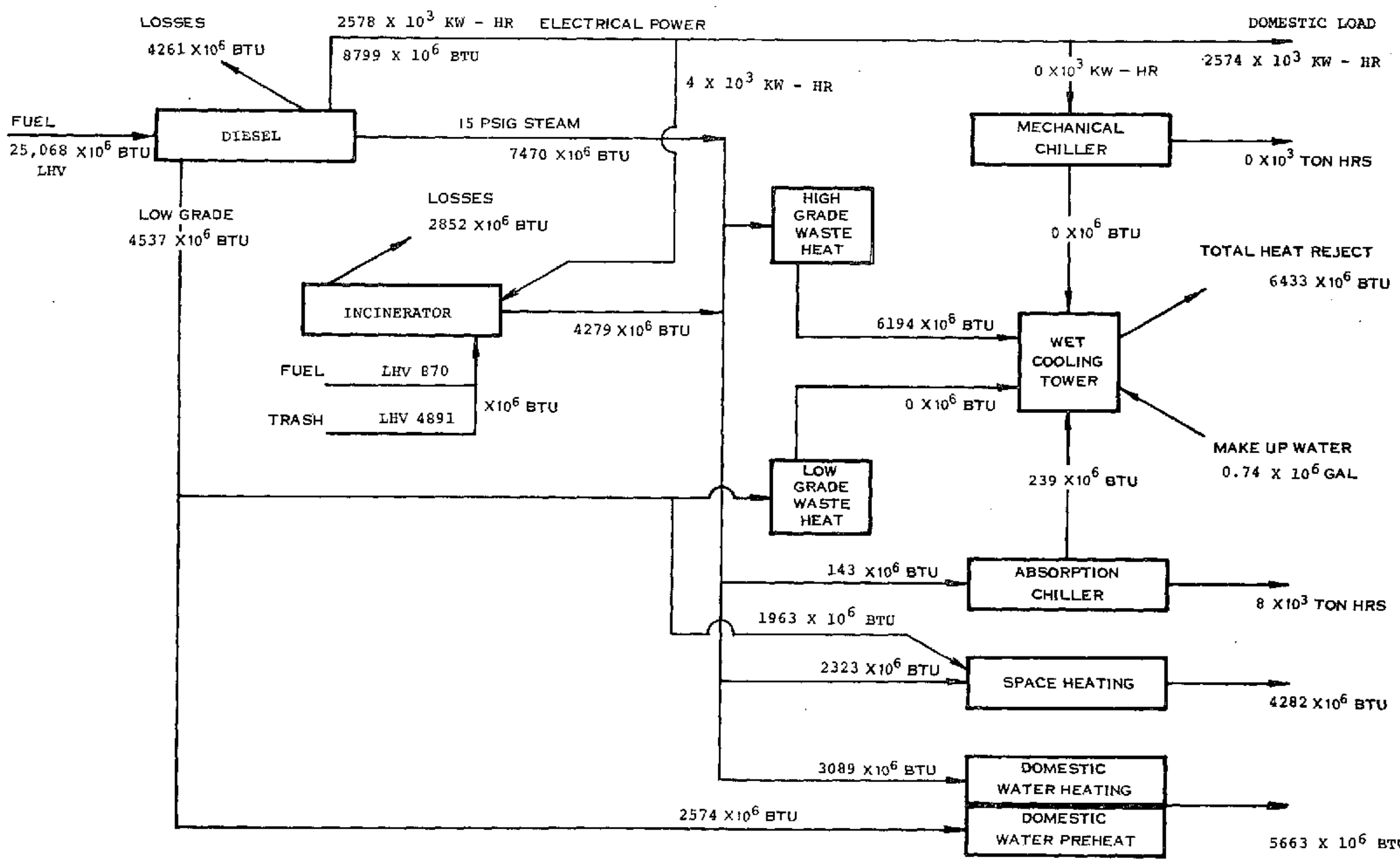
IUS BASELINE - DIESEL - SPRING
WITH INCINERATION



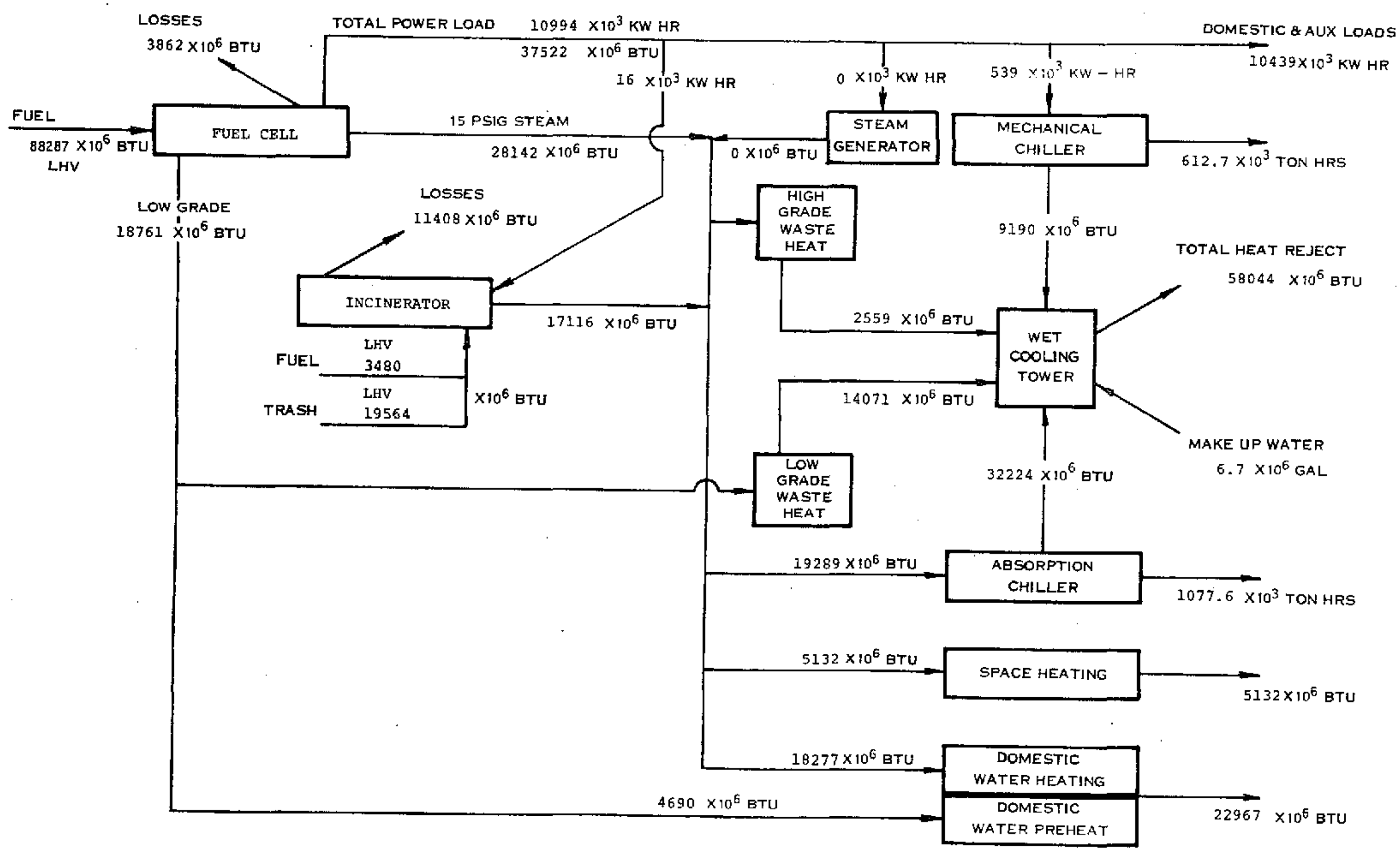
IUS BASELINE - DIESEL - SUMMER
WITH INCINERATION



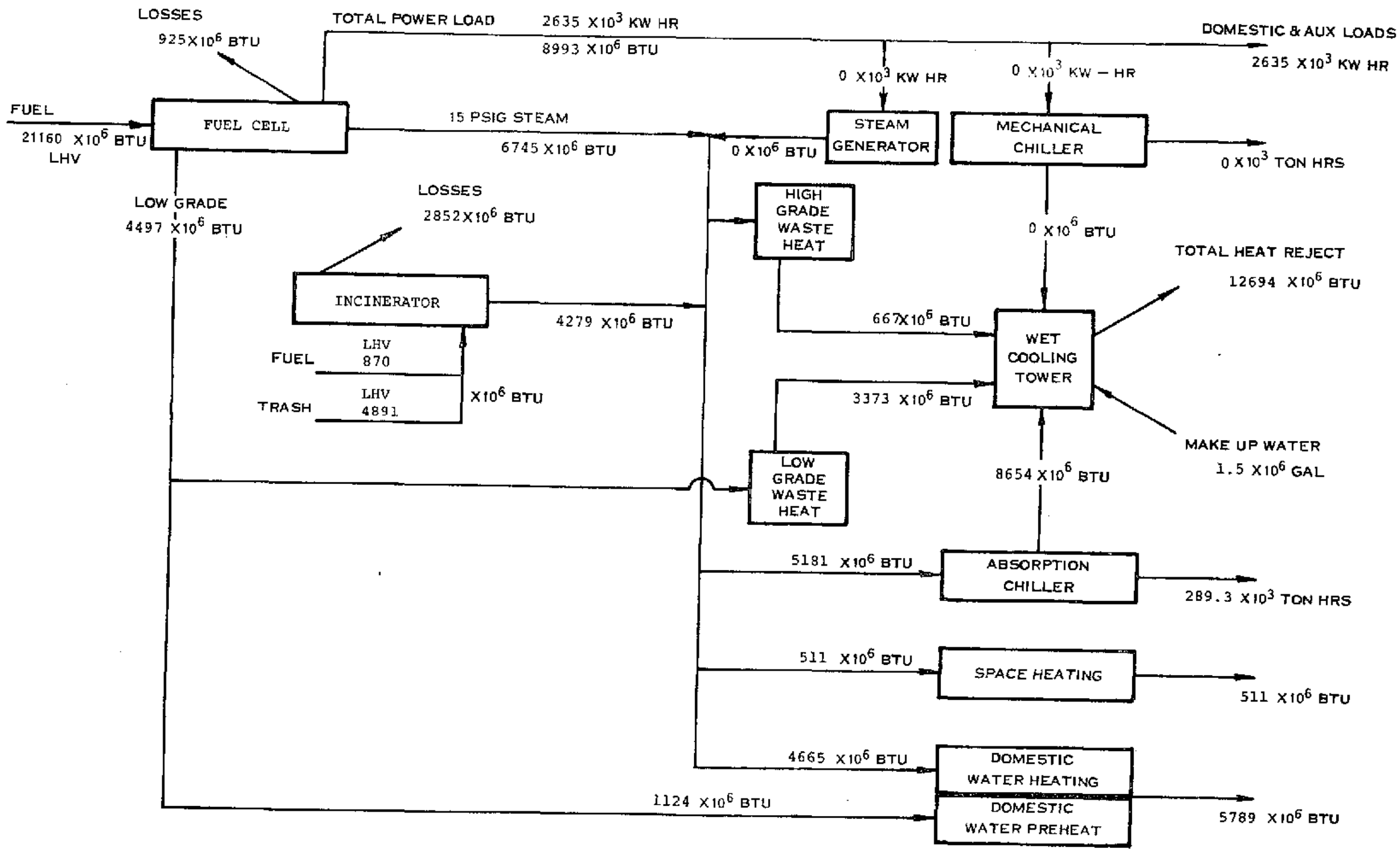
IUS BASELINE - DIESEL - FALL
WITH INCINERATION



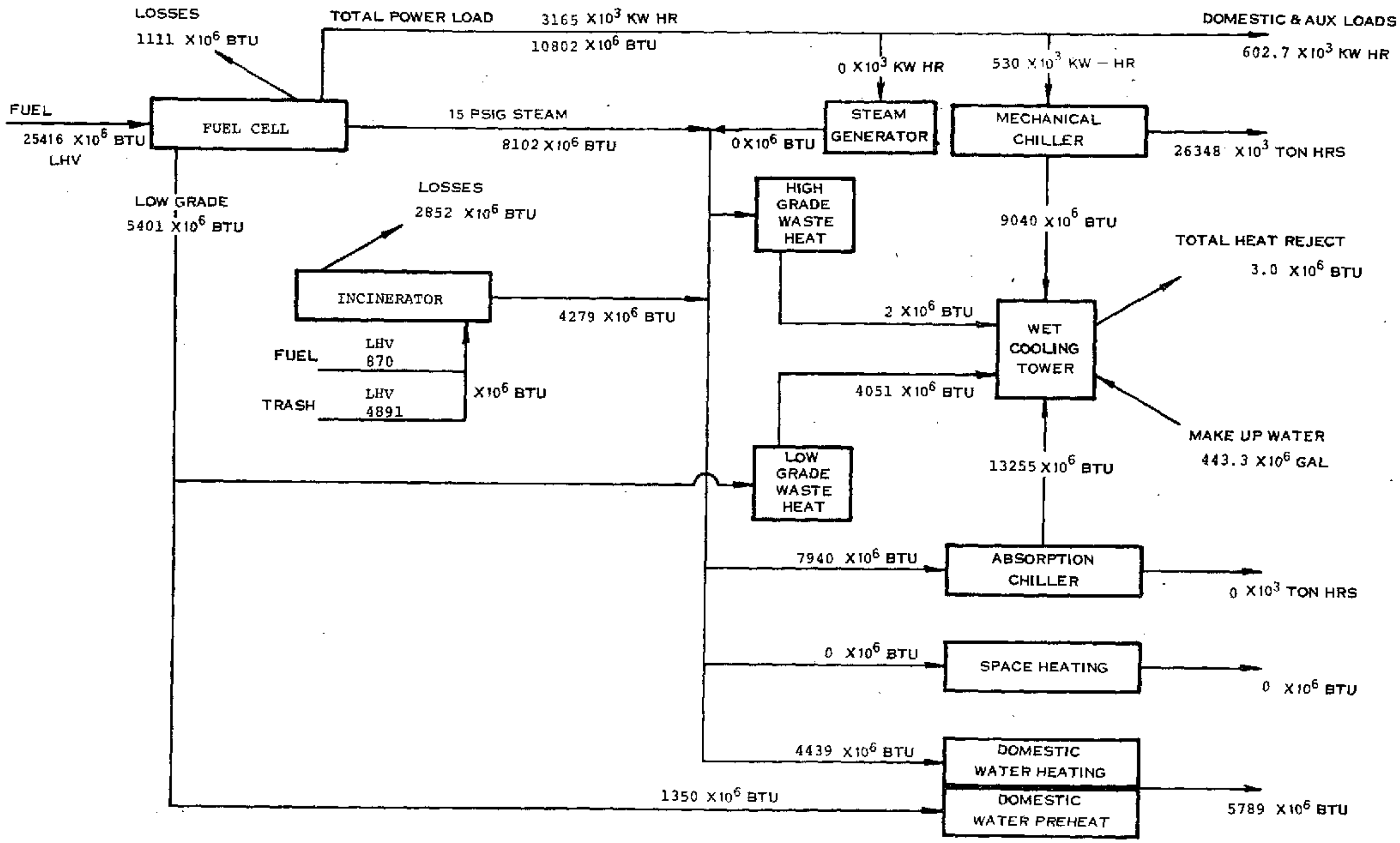
IUS BASELINE - DIESEL - WINTER
WITH INCINERATION



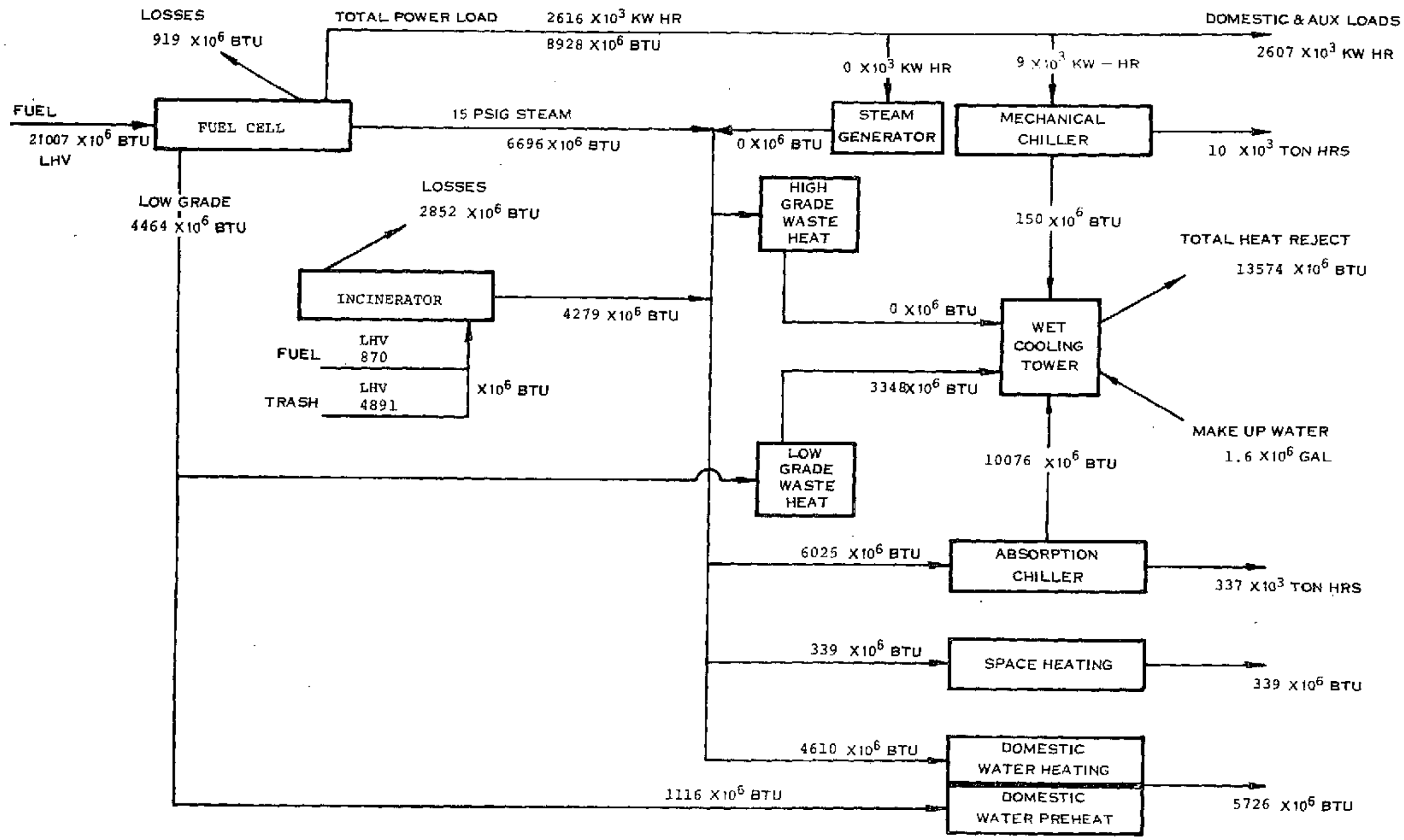
IUS - FUEL CELL - ANNUAL
WITH INCINERATOR



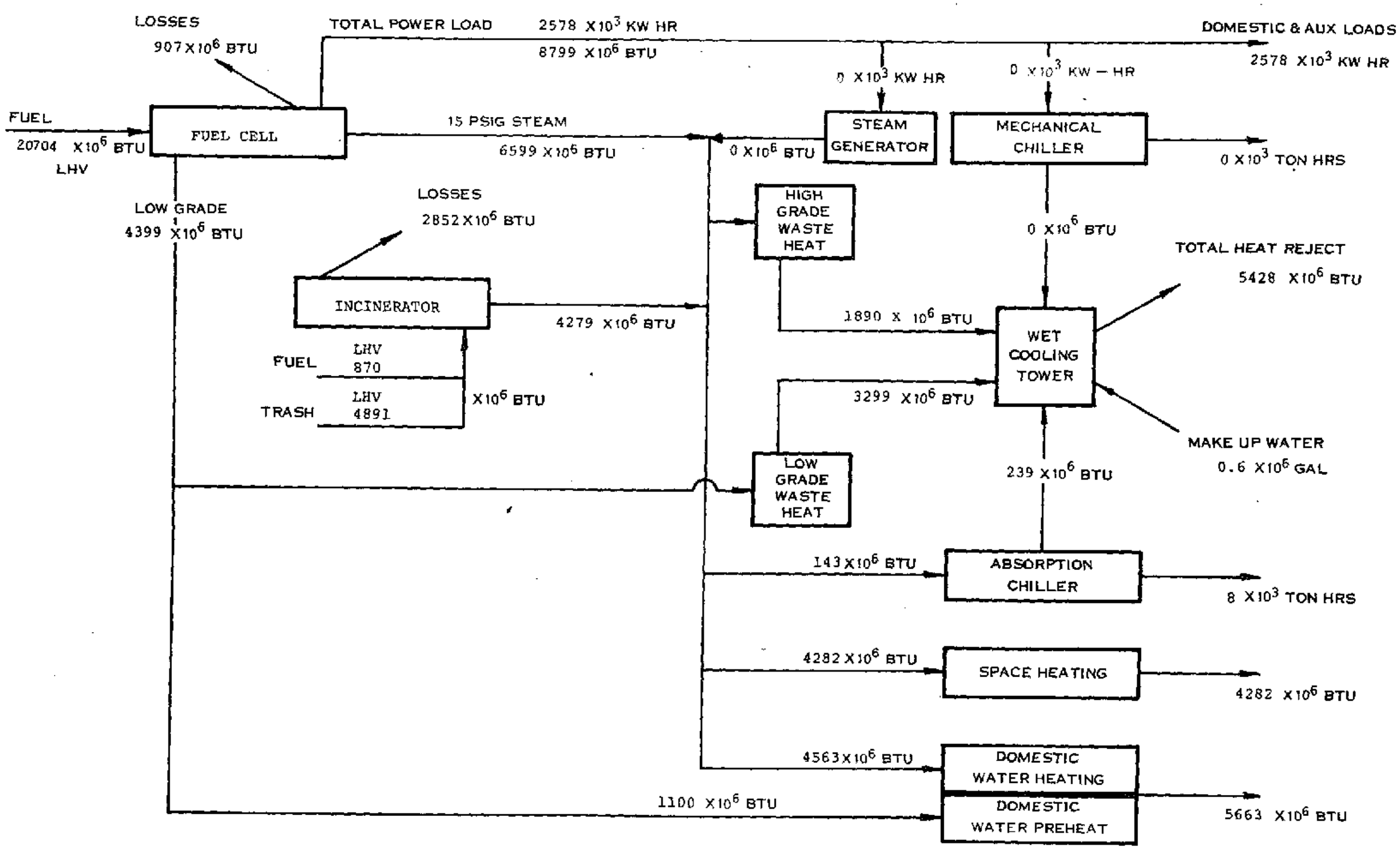
IUS - FUEL CELL - SPRING
WITH INCINERATOR



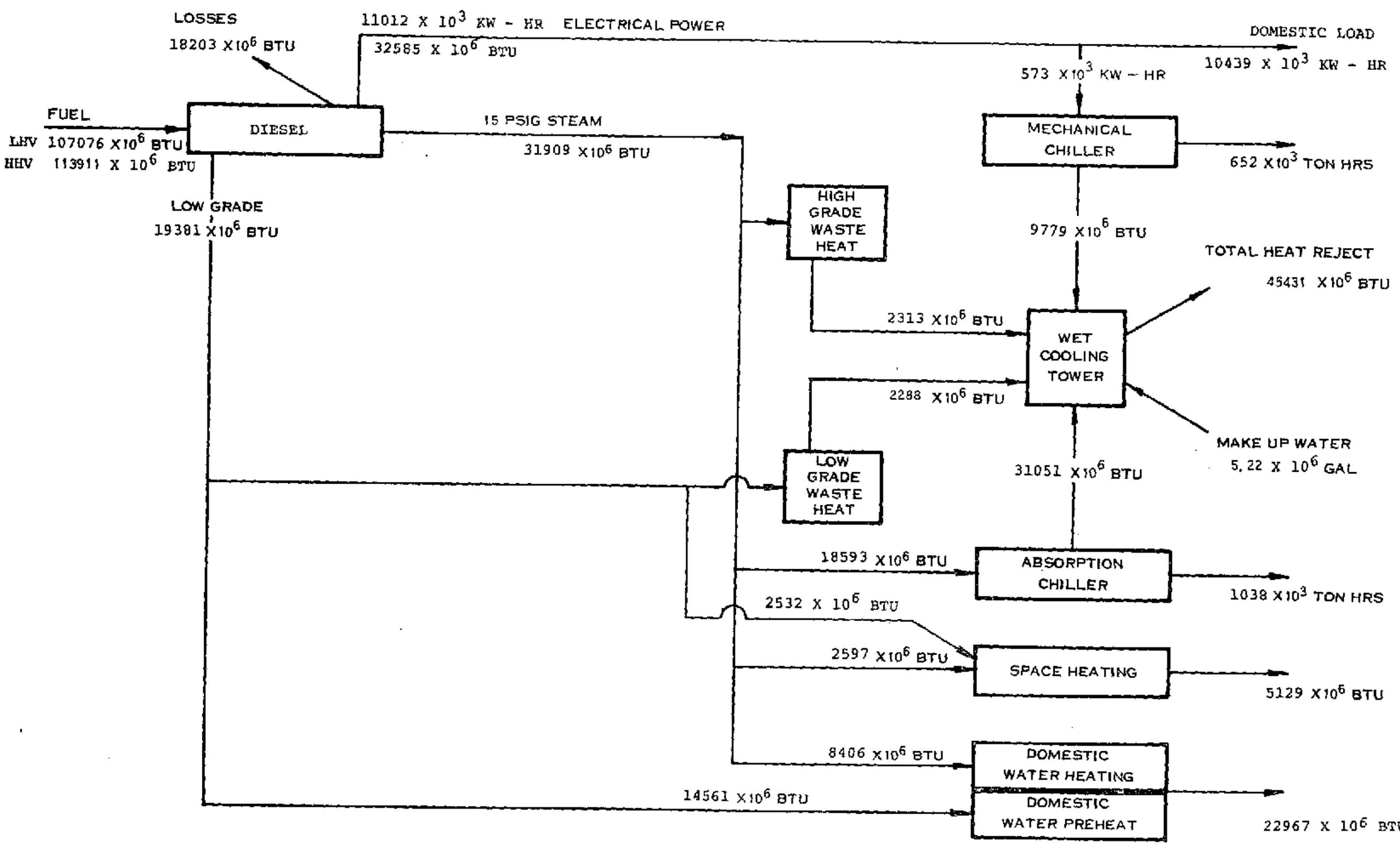
IUS - FUEL CELL - SUMMER
WITH INCINERATOR



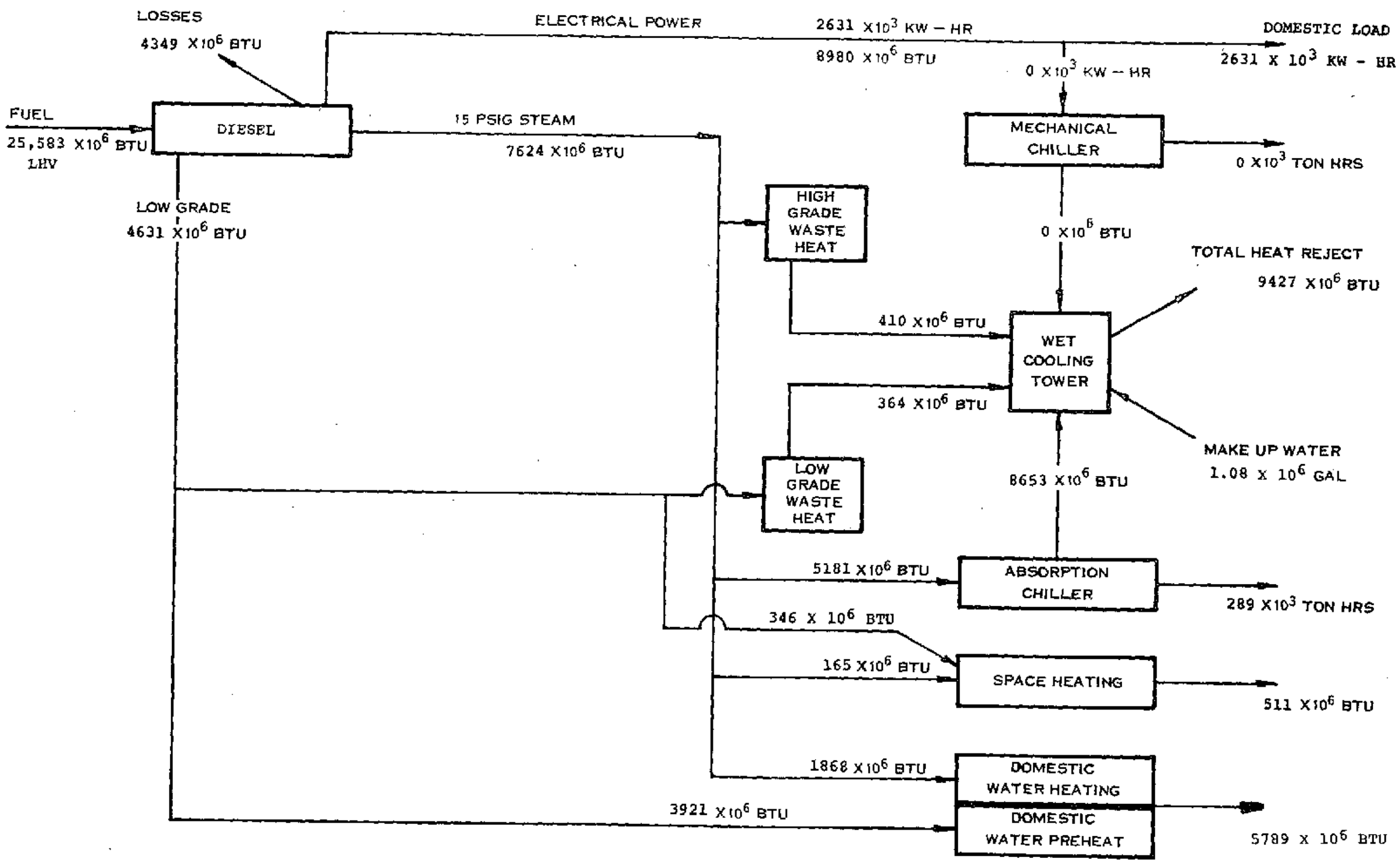
IUS - FUEL CELL - FALL
WITH INCINERATOR



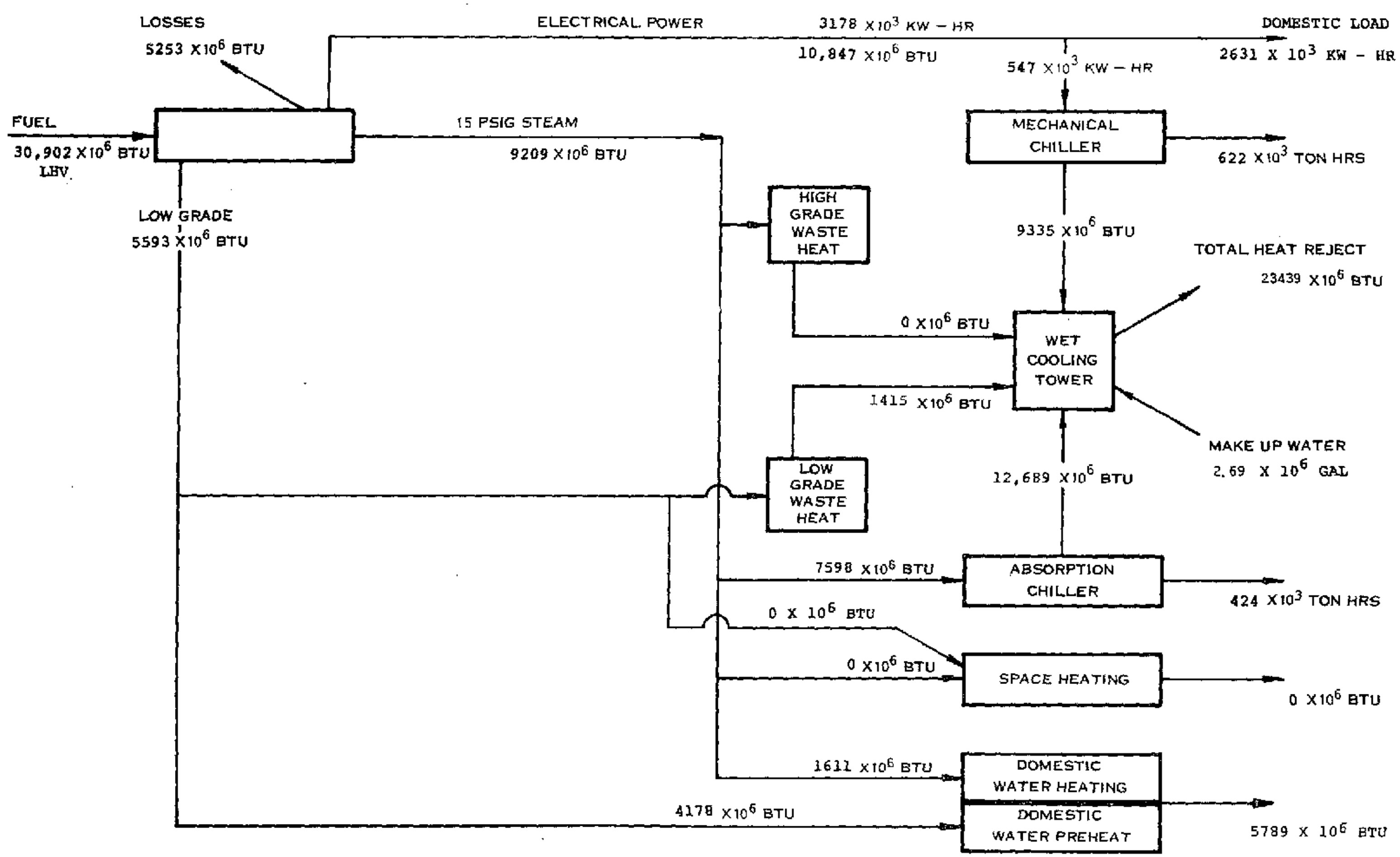
IUS - FUEL CELL - WINTER
WITH INCINERATOR



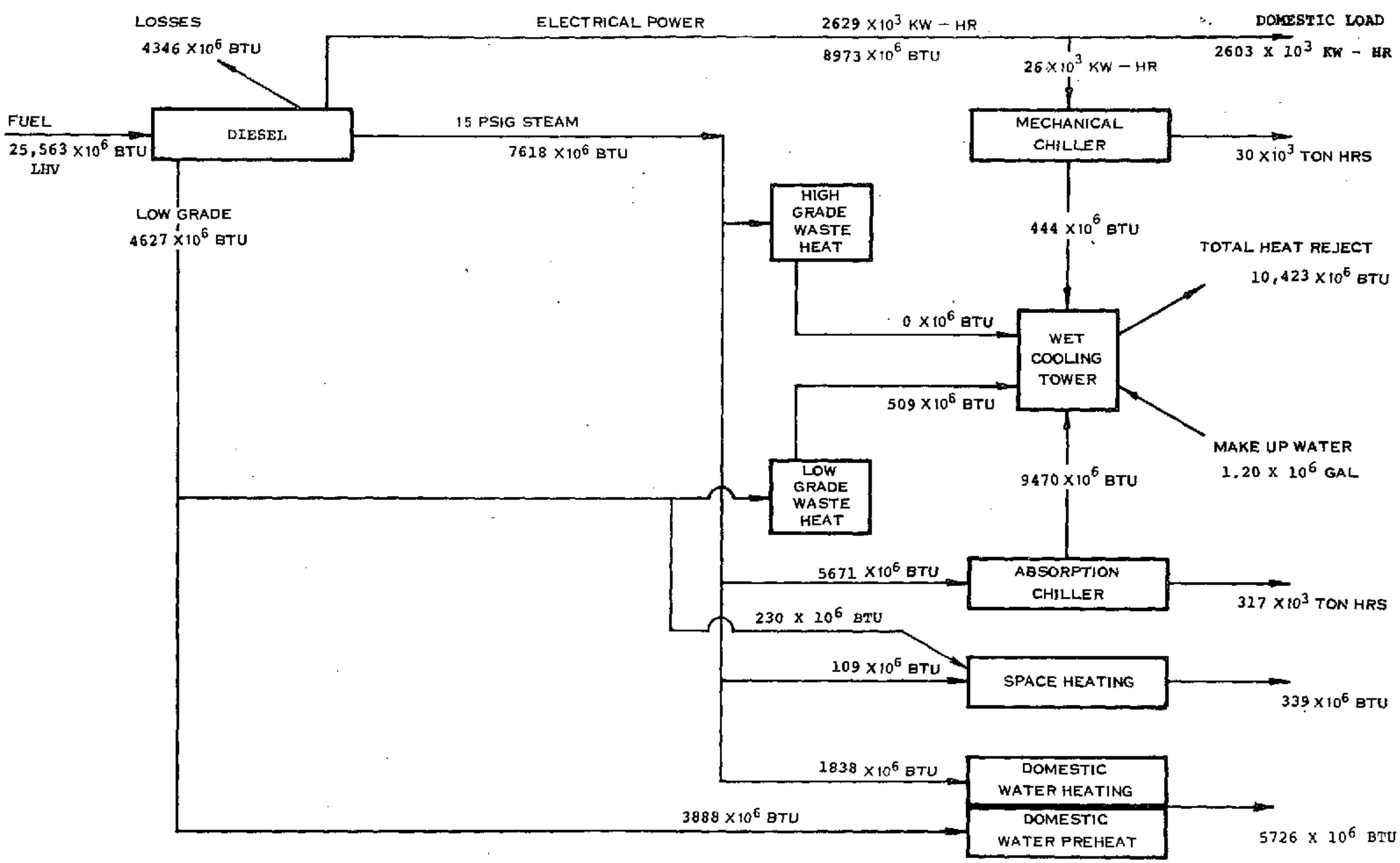
IUS - DIESEL - ANNUAL
NO WASTE DISPOSAL



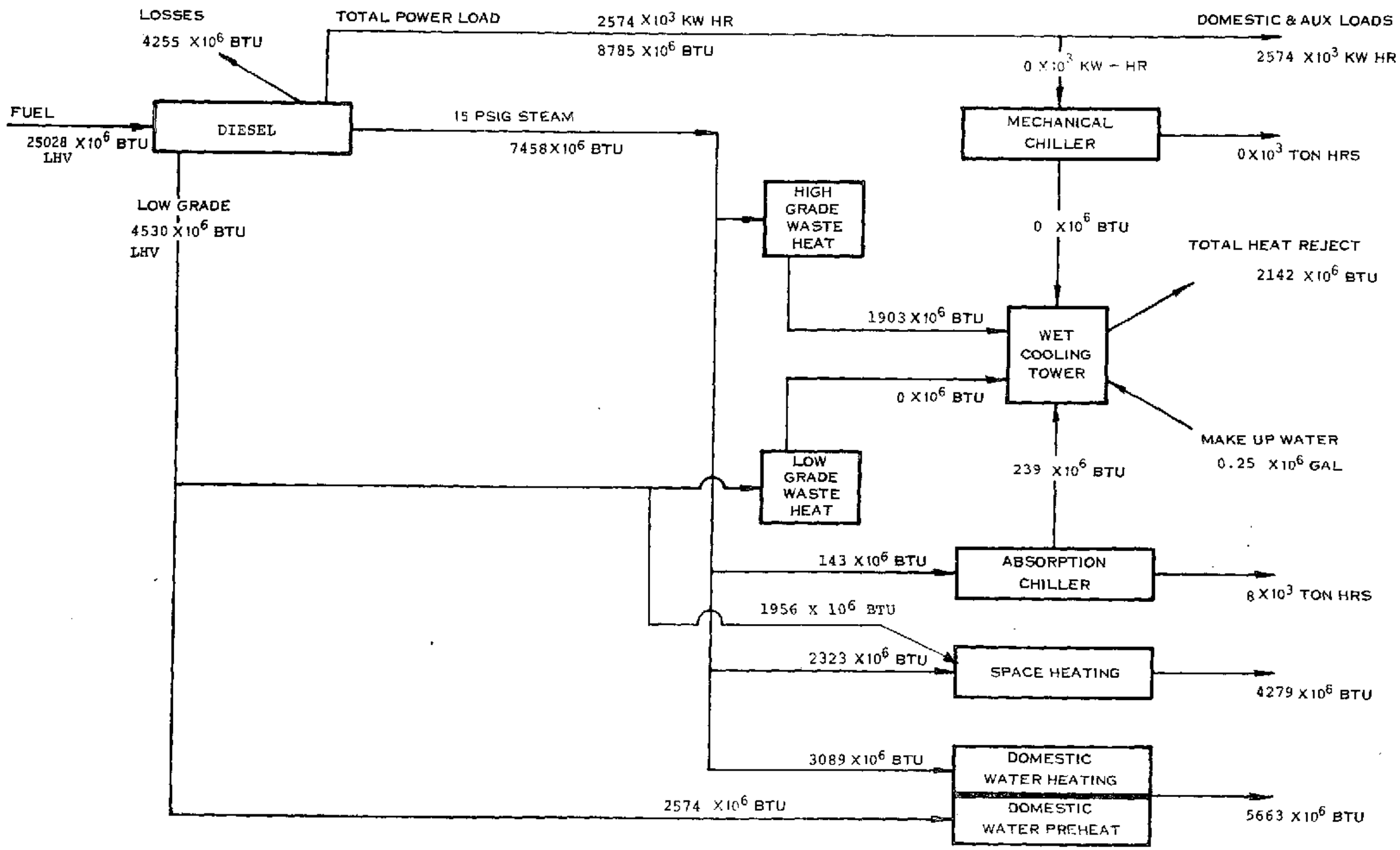
IUS - DIESEL - SPRING
NO WASTE DISPOSAL



IUS - DIESEL - SUMMER
NO WASTE DISPOSAL



DIESEL - FALL
NO WASTE DISPOSAL



IUS - DIESEL - WINTER
NO WASTE DISPOSAL

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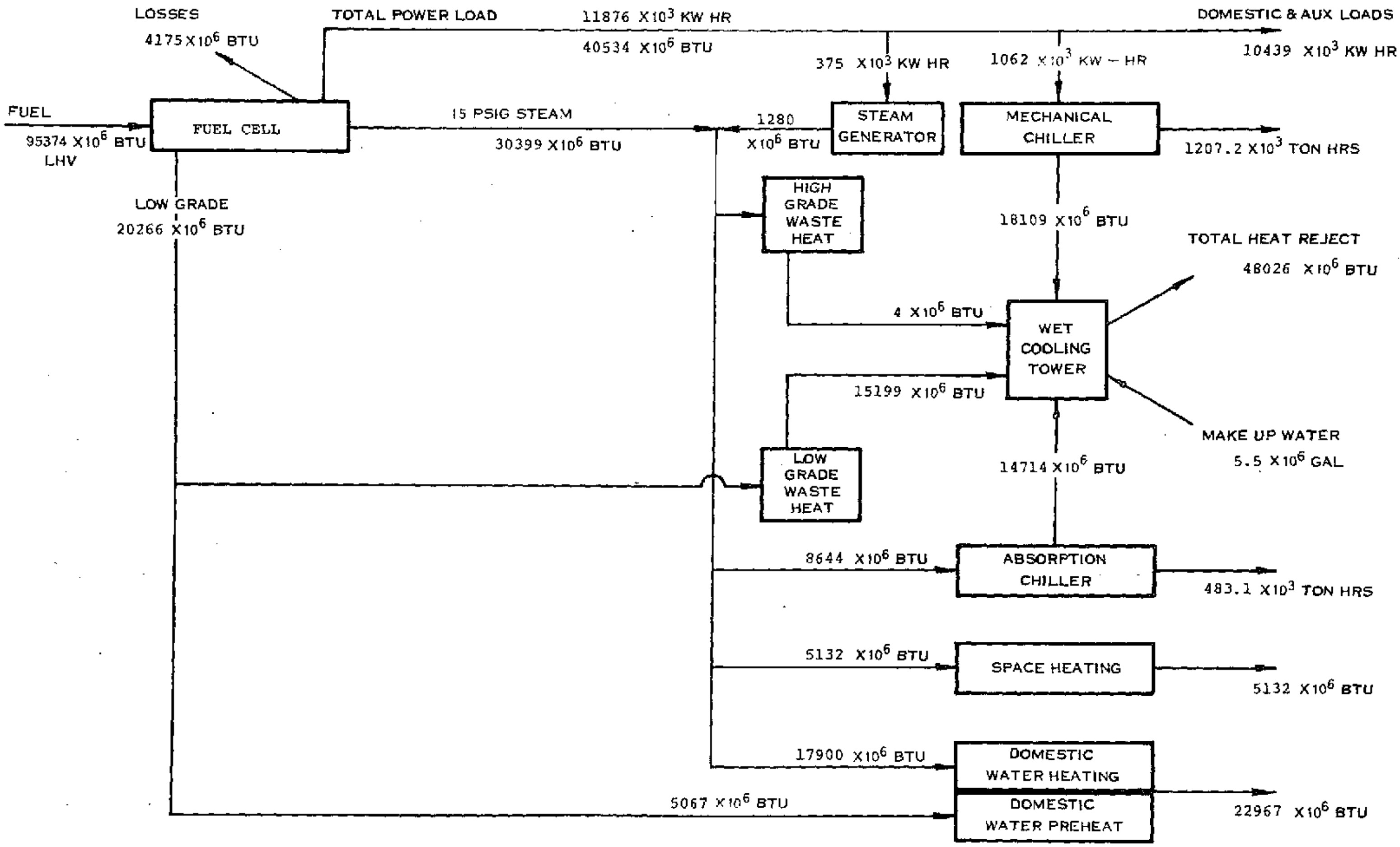
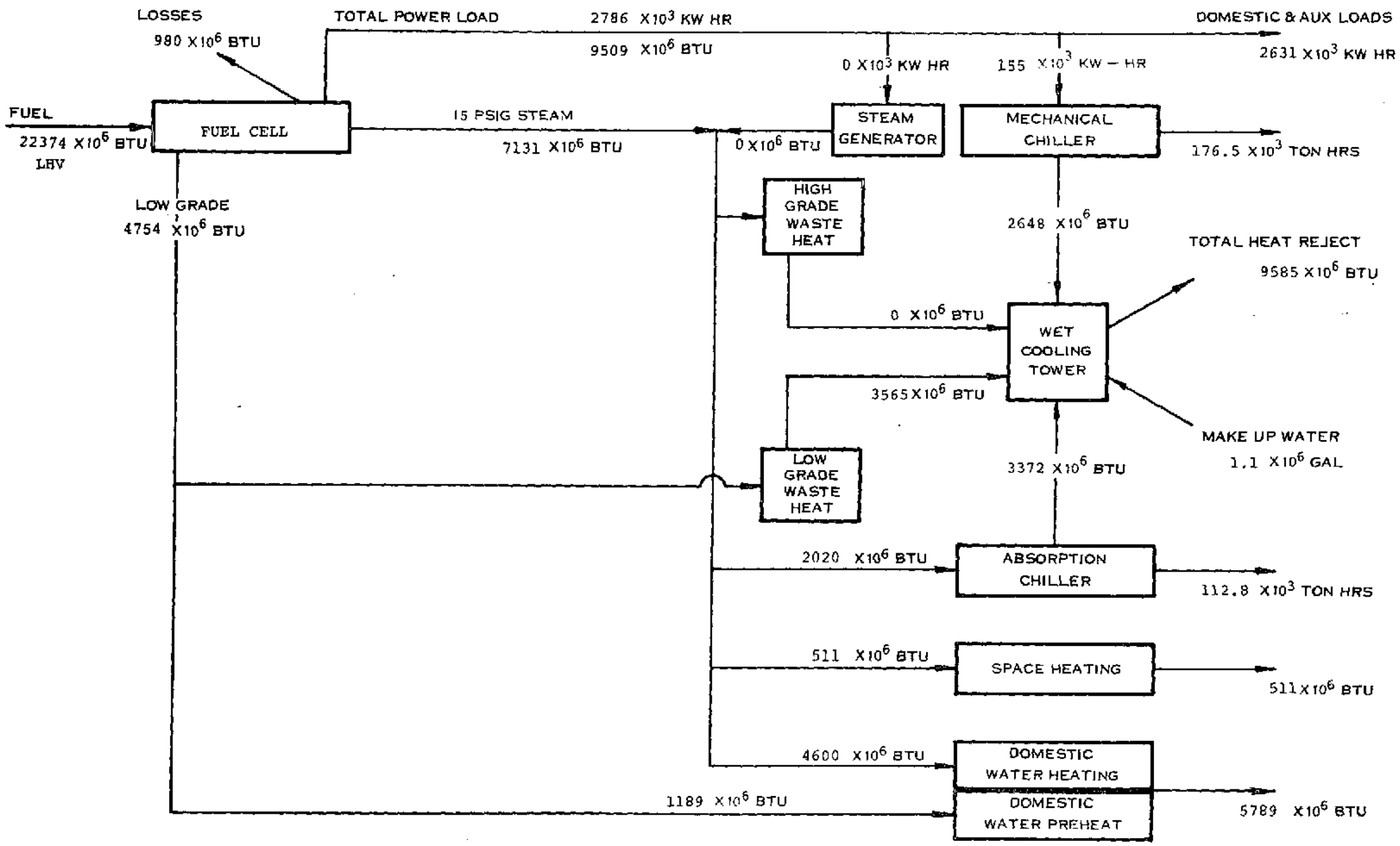
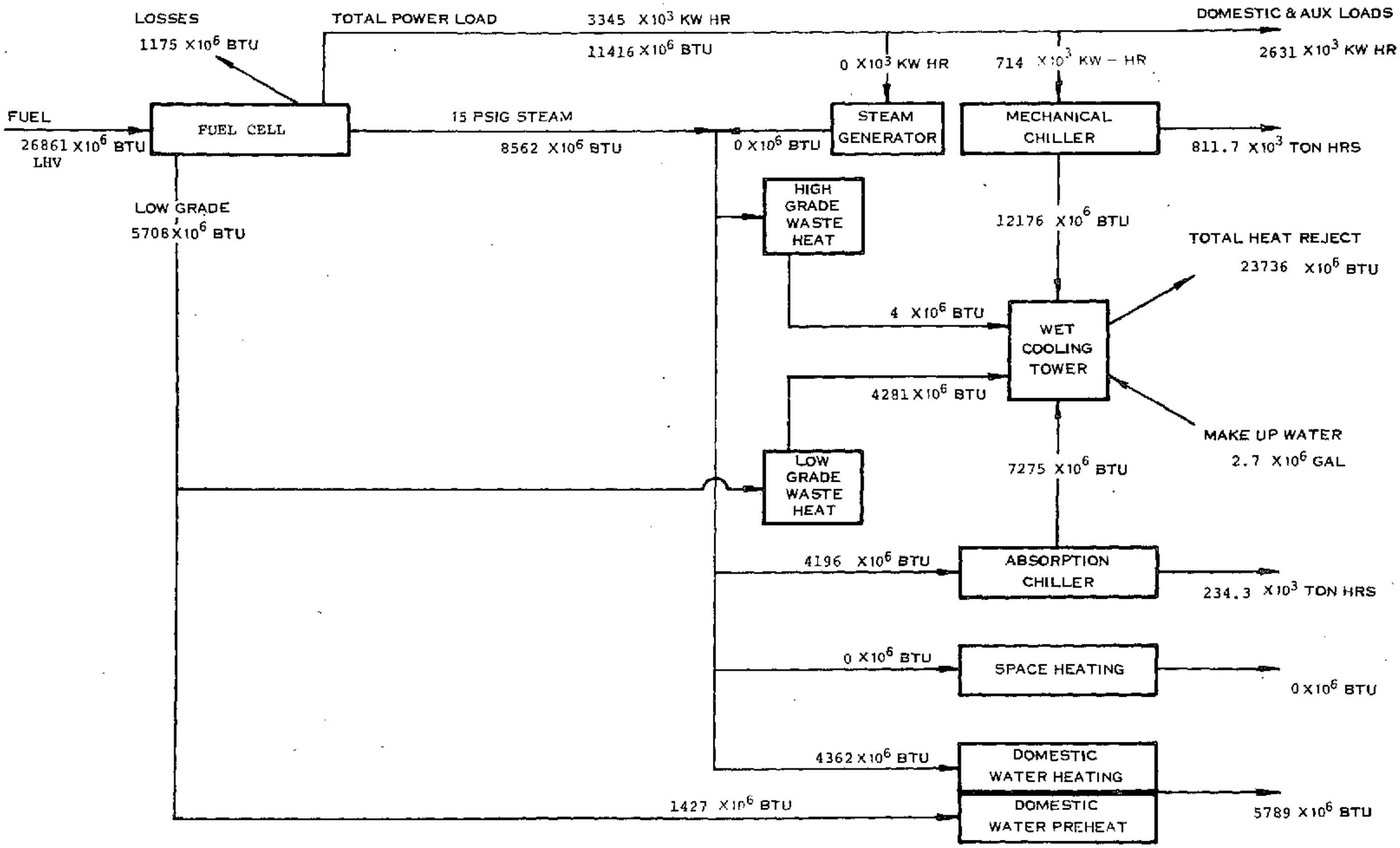


IUS - FUEL CELL - ANNUAL

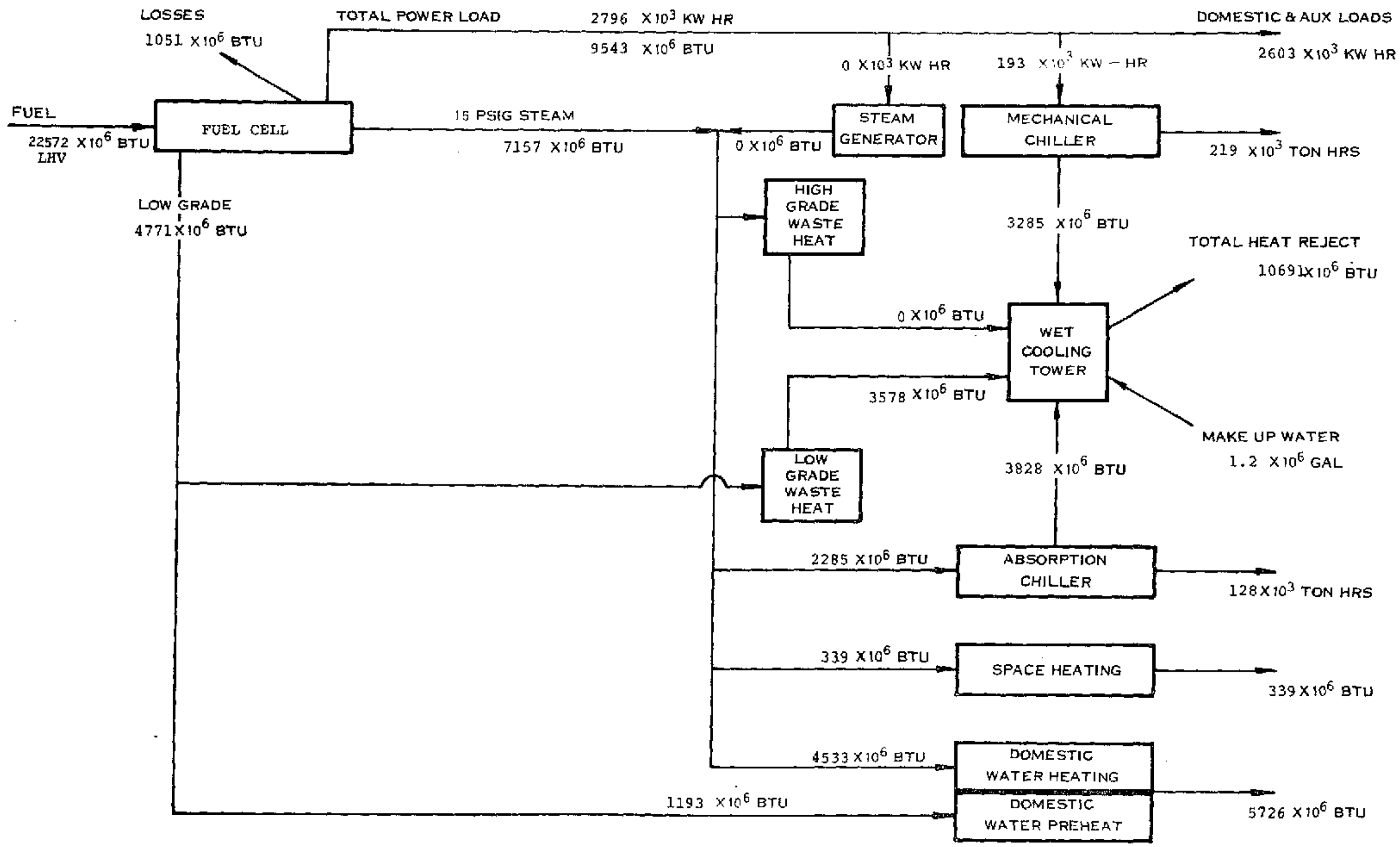
NO SOLID WASTE DISPOSAL



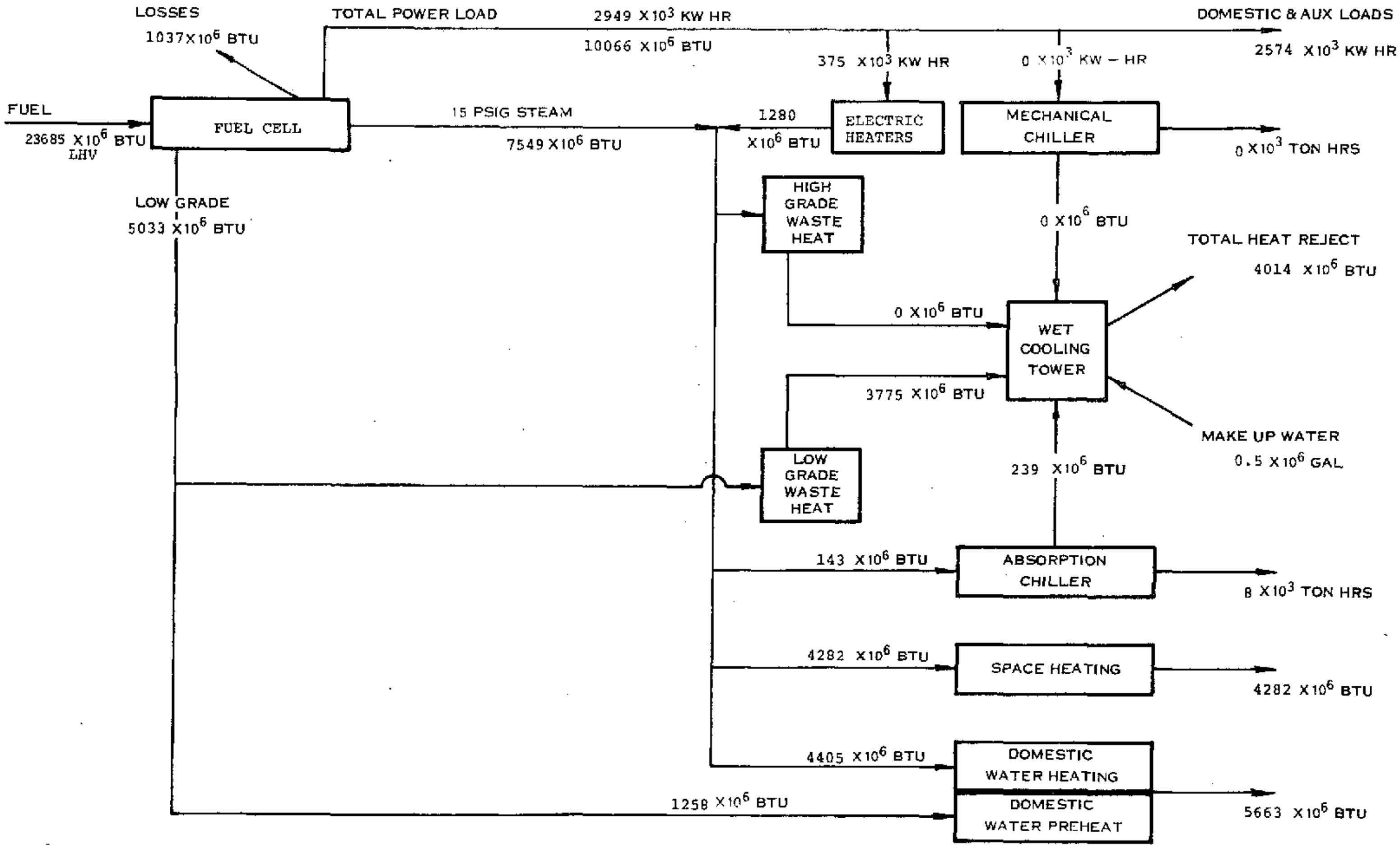
IUS - FUEL CELL - SPRING
NO SOLID WASTE DISPOSAL



IUS - FUEL CELL - SUMMER
NO WASTE DISPOSAL



IUS - FUEL CELL - FALL
NO WASTE DISPOSAL



IUS – FUEL CELL – WINTER
NO SOLID WASTE DISPOSAL

APPENDIX E1

PYROLYSIS/IUS FLOW CHART MODELS

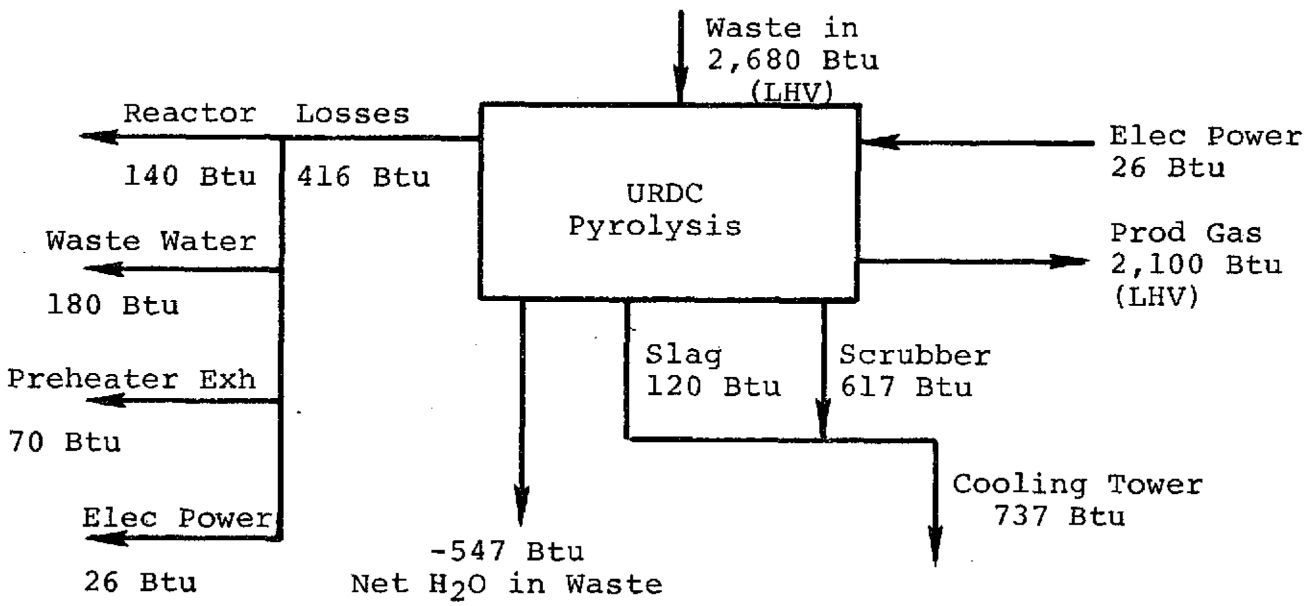
E1

PYROLYSIS FLOW CHART MODELS

The following pyrolysis energy balance models were used in the Pyrolysis/IUS flow charts.

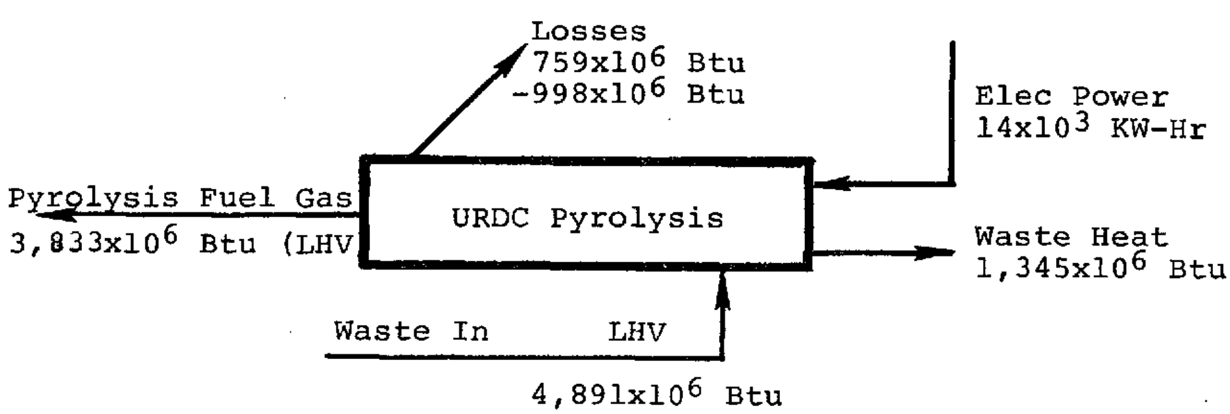
URDC Pyrolysis System

Per Pound Waste Input



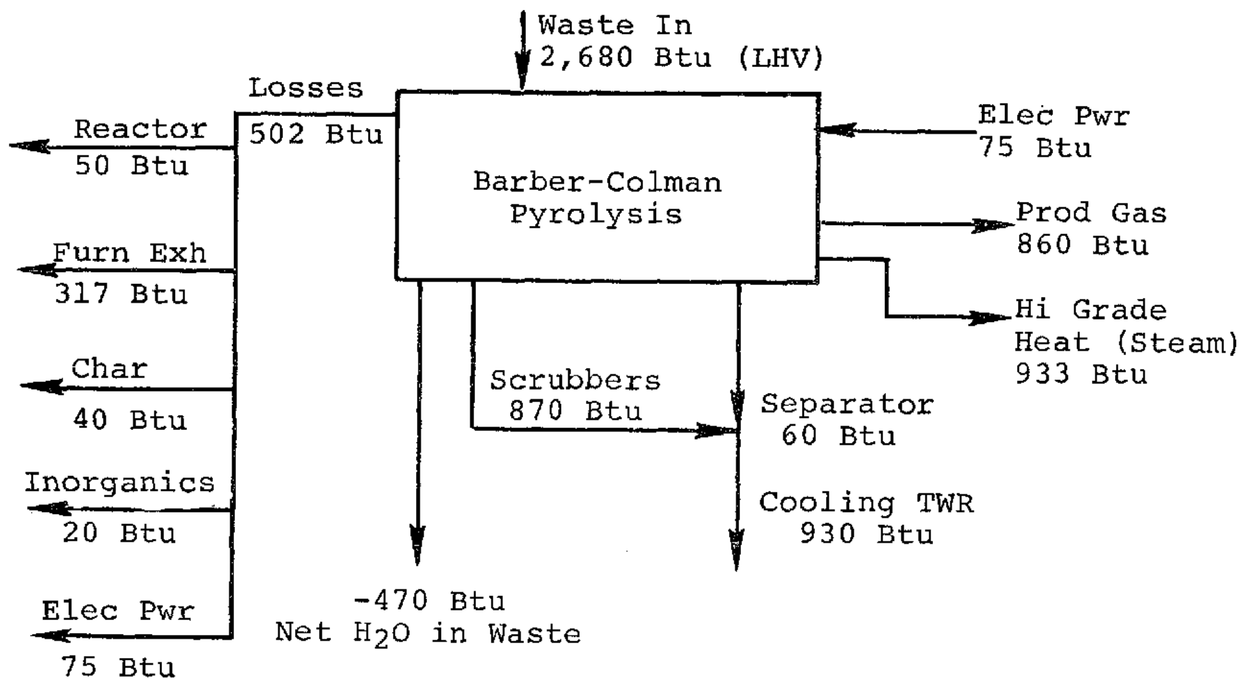
Seasonal Basis

(1.825×10^6 Lb Waste Input/Season)



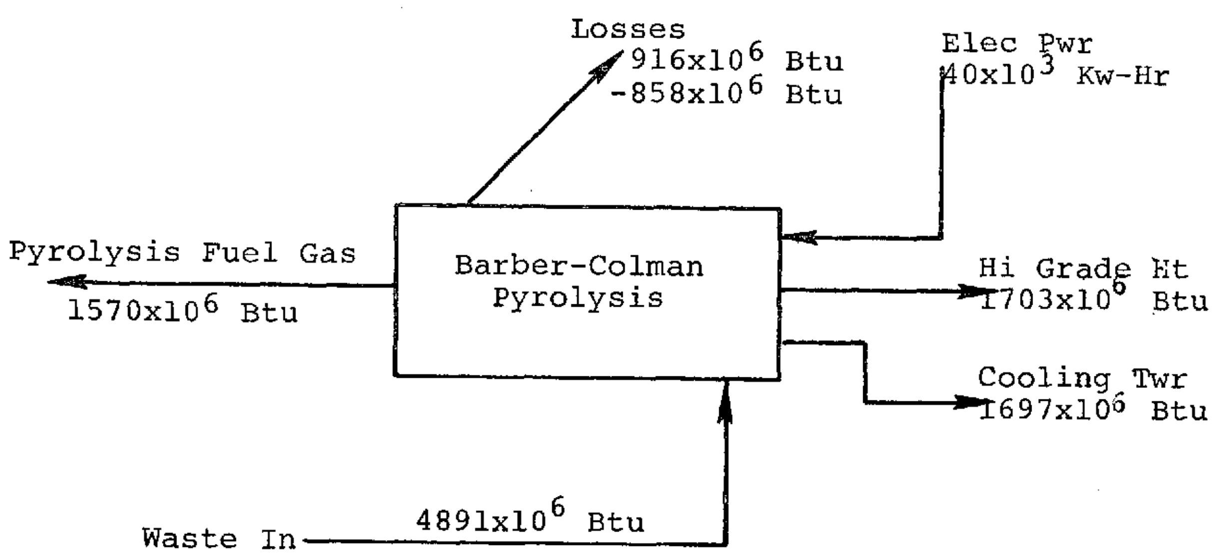
Barber-Colman Pyrolysis System

Per Pound Waste Input



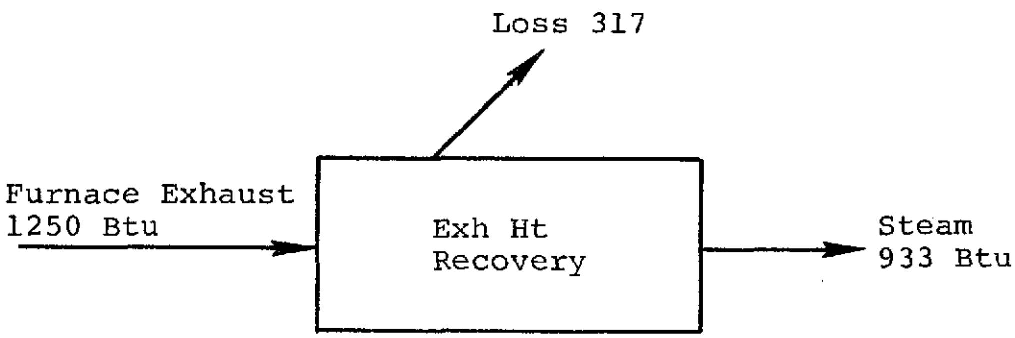
Seasonal Basis

(1.825×10^6 Lb Waste Input/Season)



Barber-Colman Pyrolysis System

Steam Recovery/Pound Waste Input



Based On Cooling From 1400°F to 400°F

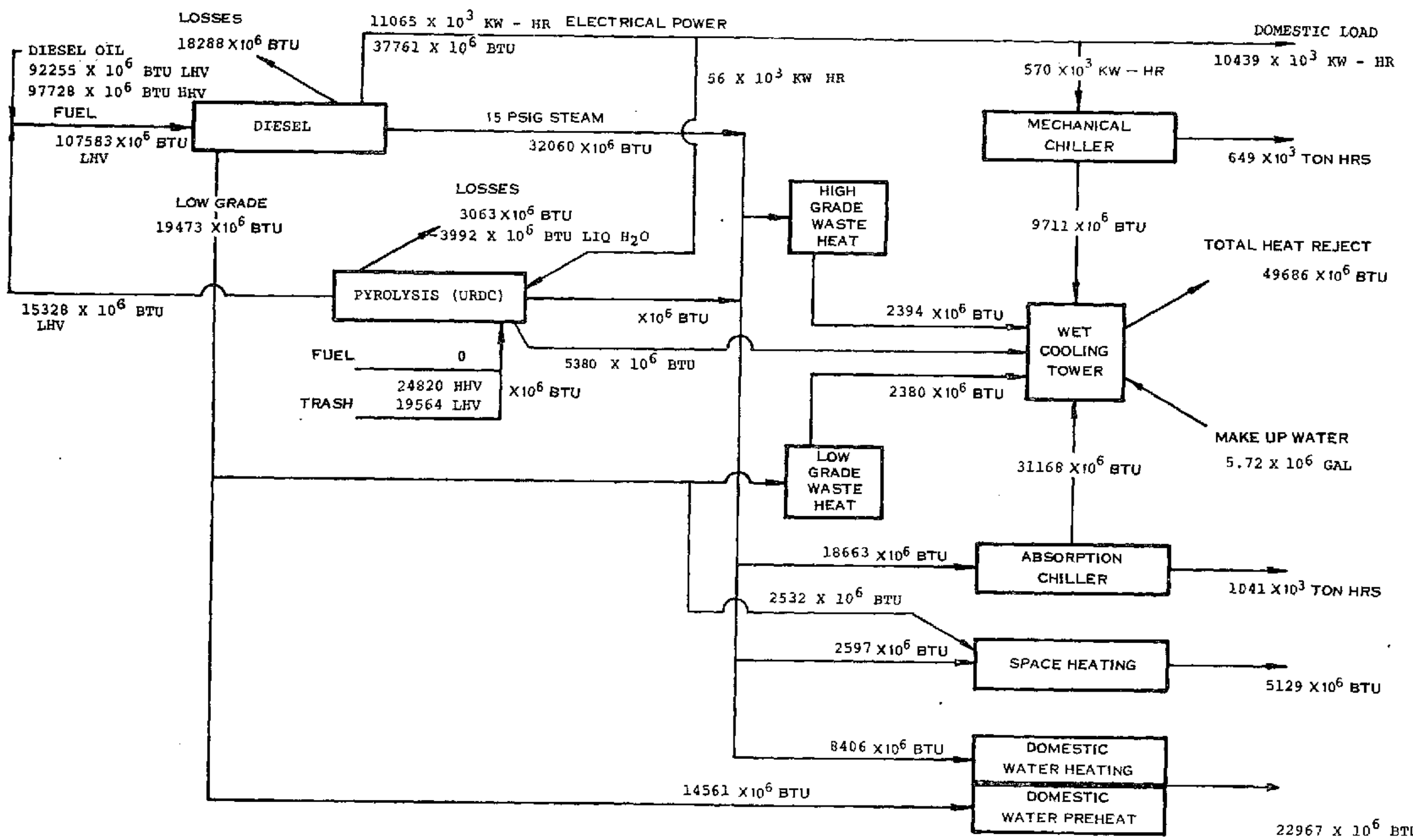
APPENDIX E2

INTEGRATED PYROLYSIS/IUS PERFORMANCE FLOW CHARTS

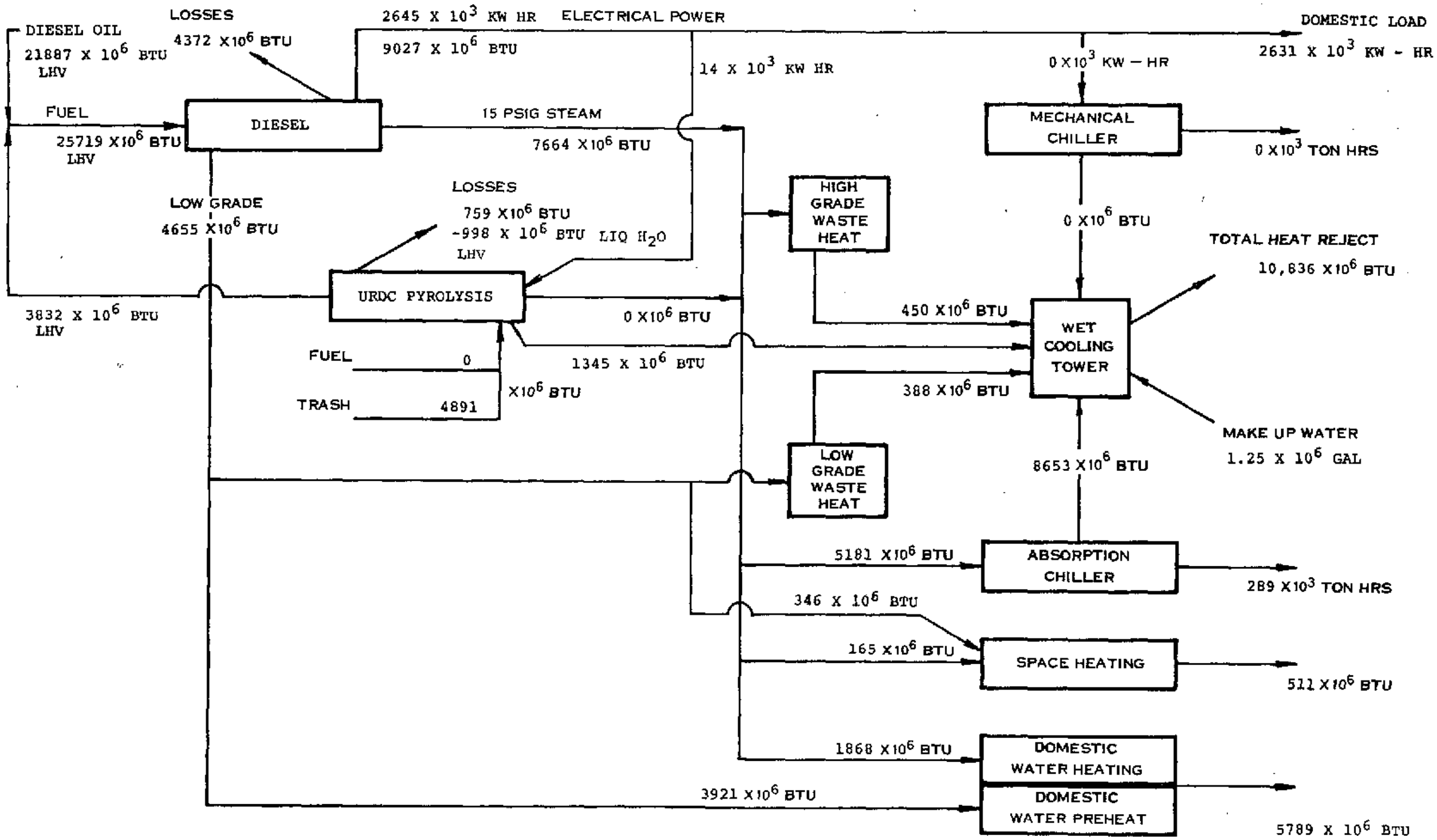
E2

INTEGRATED PYROLYSIS/IUS PERFORMANCE FLOW CHARTS

The charts which follow illustrate the energy utilization of a 1000 Unit Apartment Complex IUS with integrated pyrolysis for solid waste disposal. Both URDC and Barber-Colman pyrolysis systems are considered. Each pyrolysis/IUS configuration is analyzed with both fuel cell and diesel electrical power generation. The analyses were conducted on a seasonal basis, and an annual summary for each configuration was prepared from the seasonal results.



IUS - DIESEL - ANNUAL
WITH PYROLYSIS (URDC)



IUS - DIESEL - SPRING
WITH PYROLYSIS (URDC)

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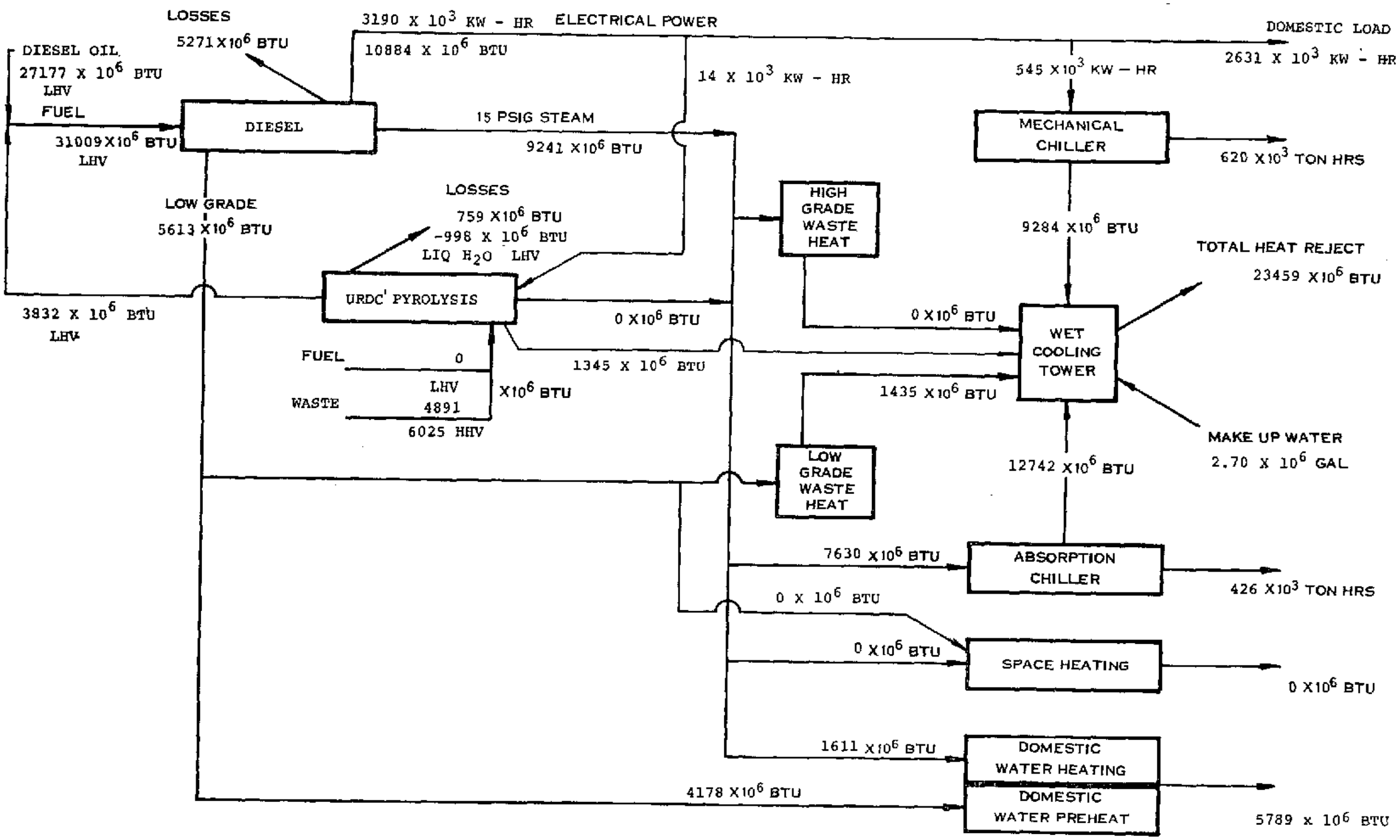

IUS - DIESEL - SUMMER
WITH PYROLYSIS (URDC)

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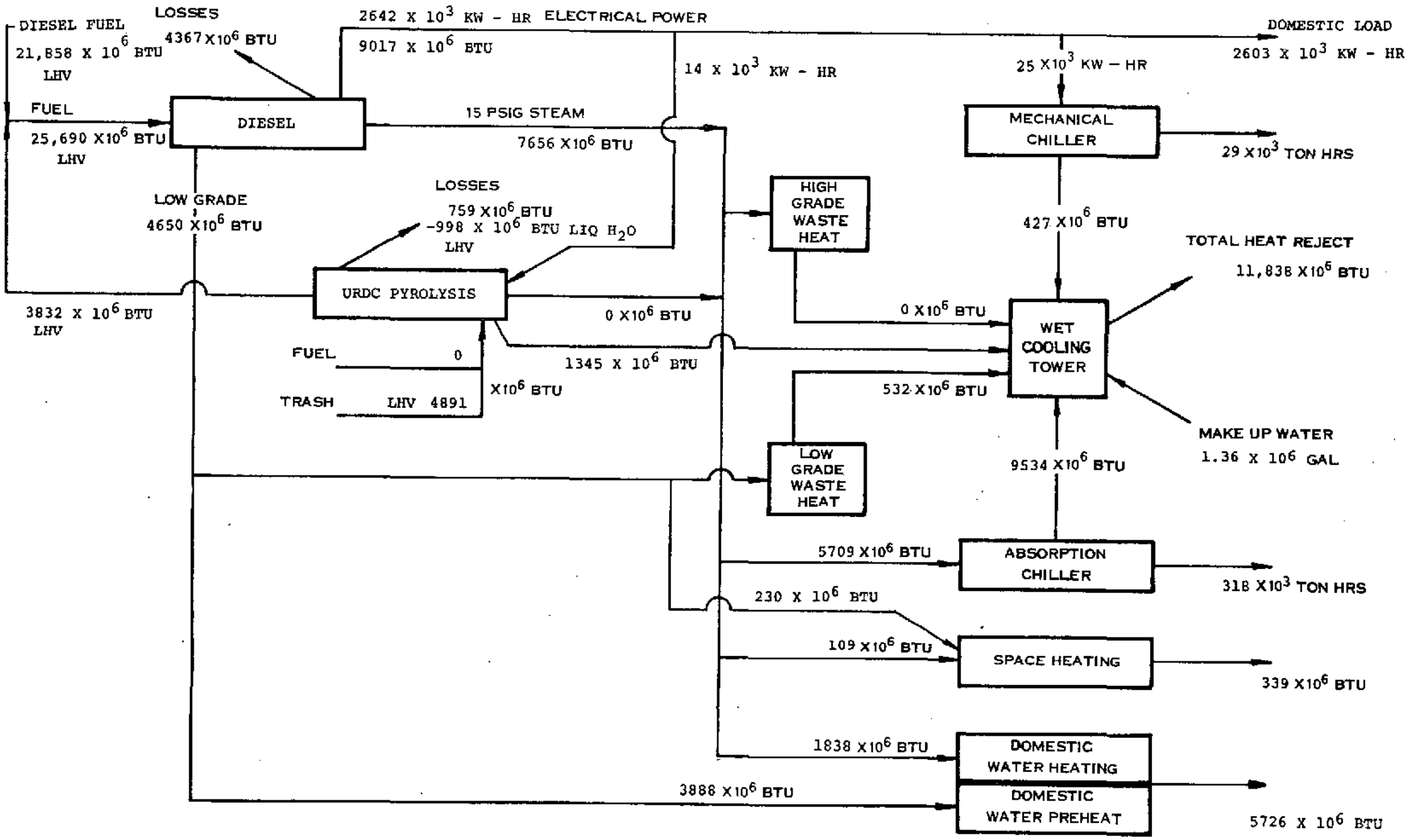
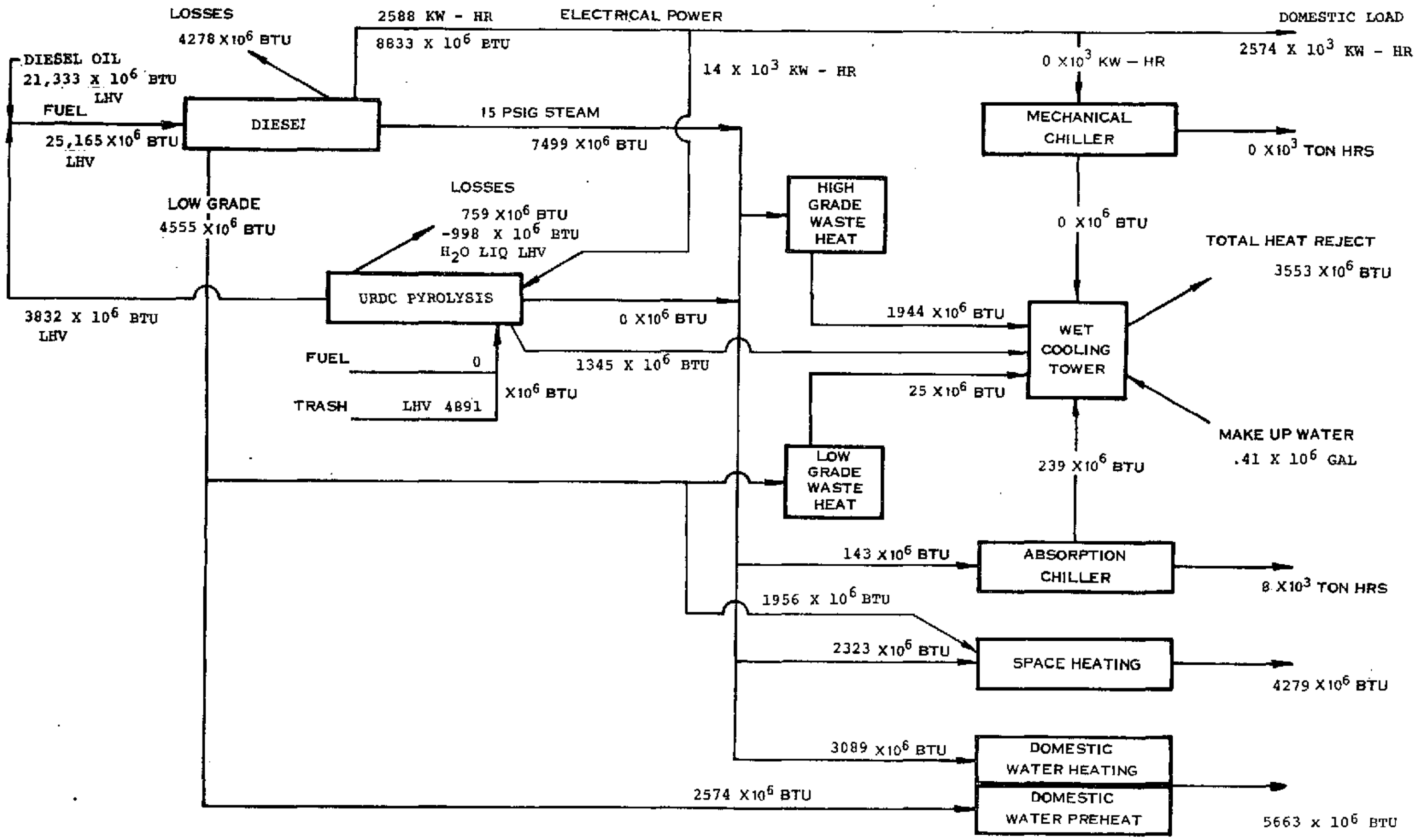
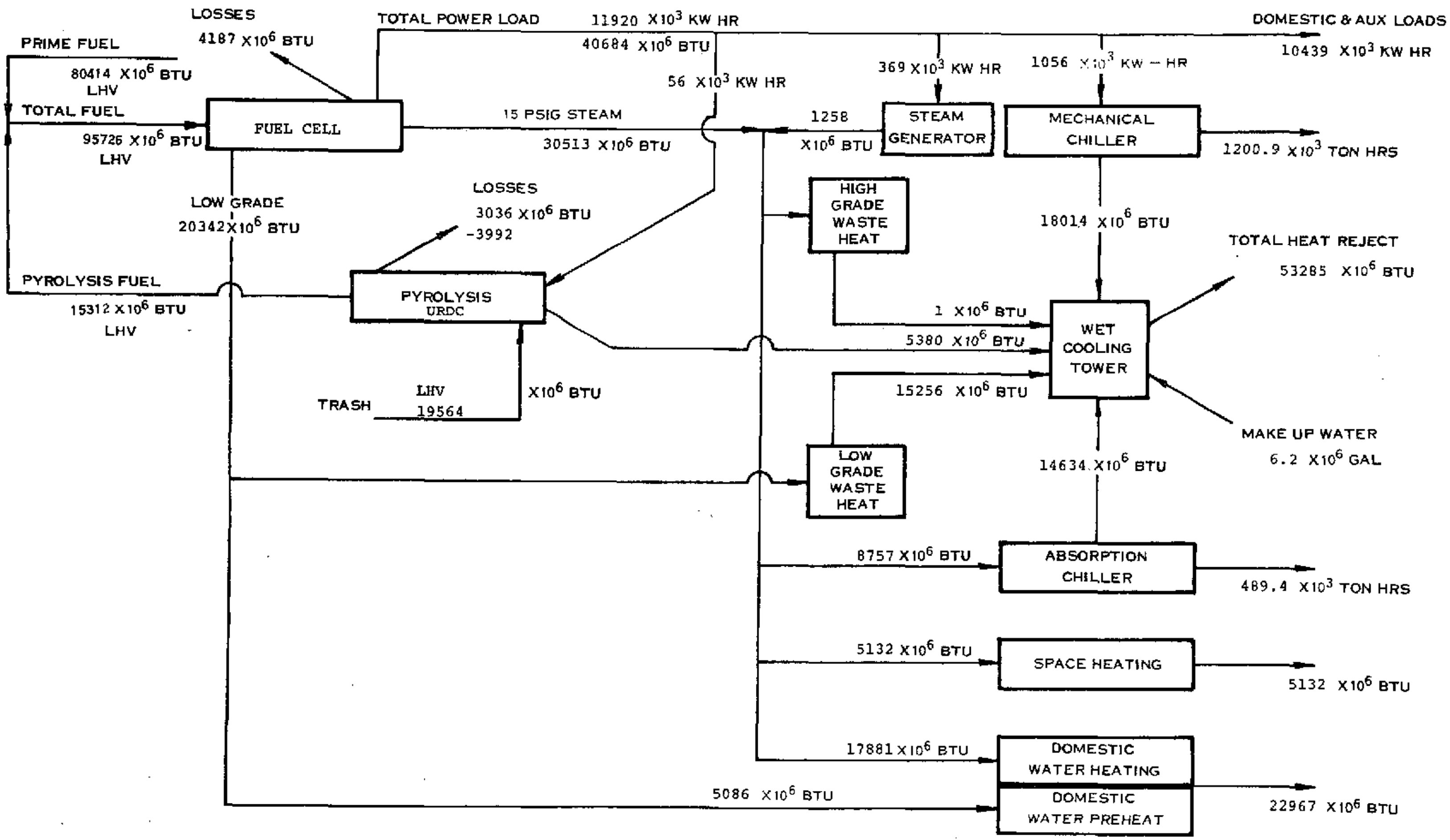


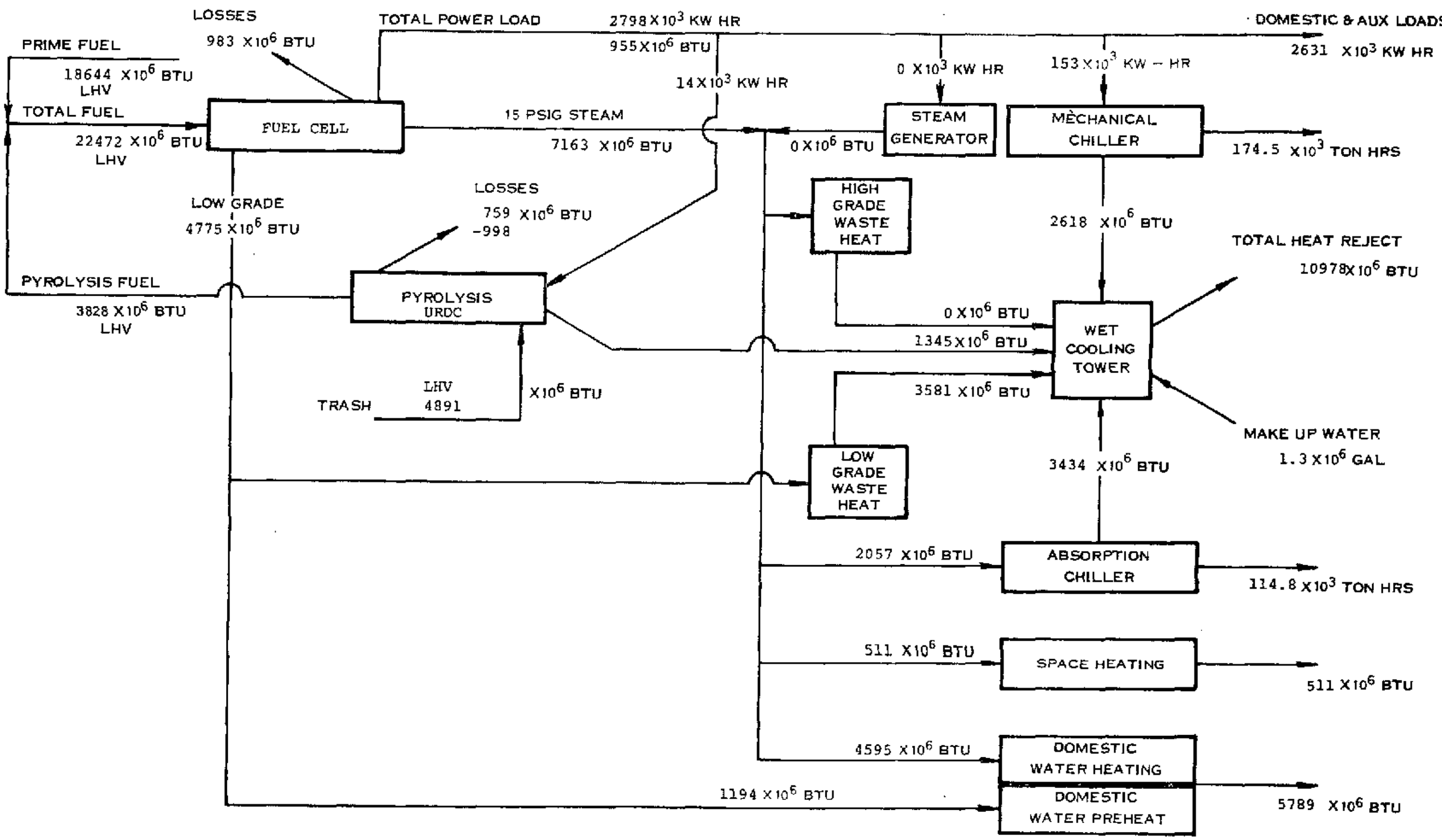
IUS - DIESEL - FALL
WITH PYROLYSIS (URDC)



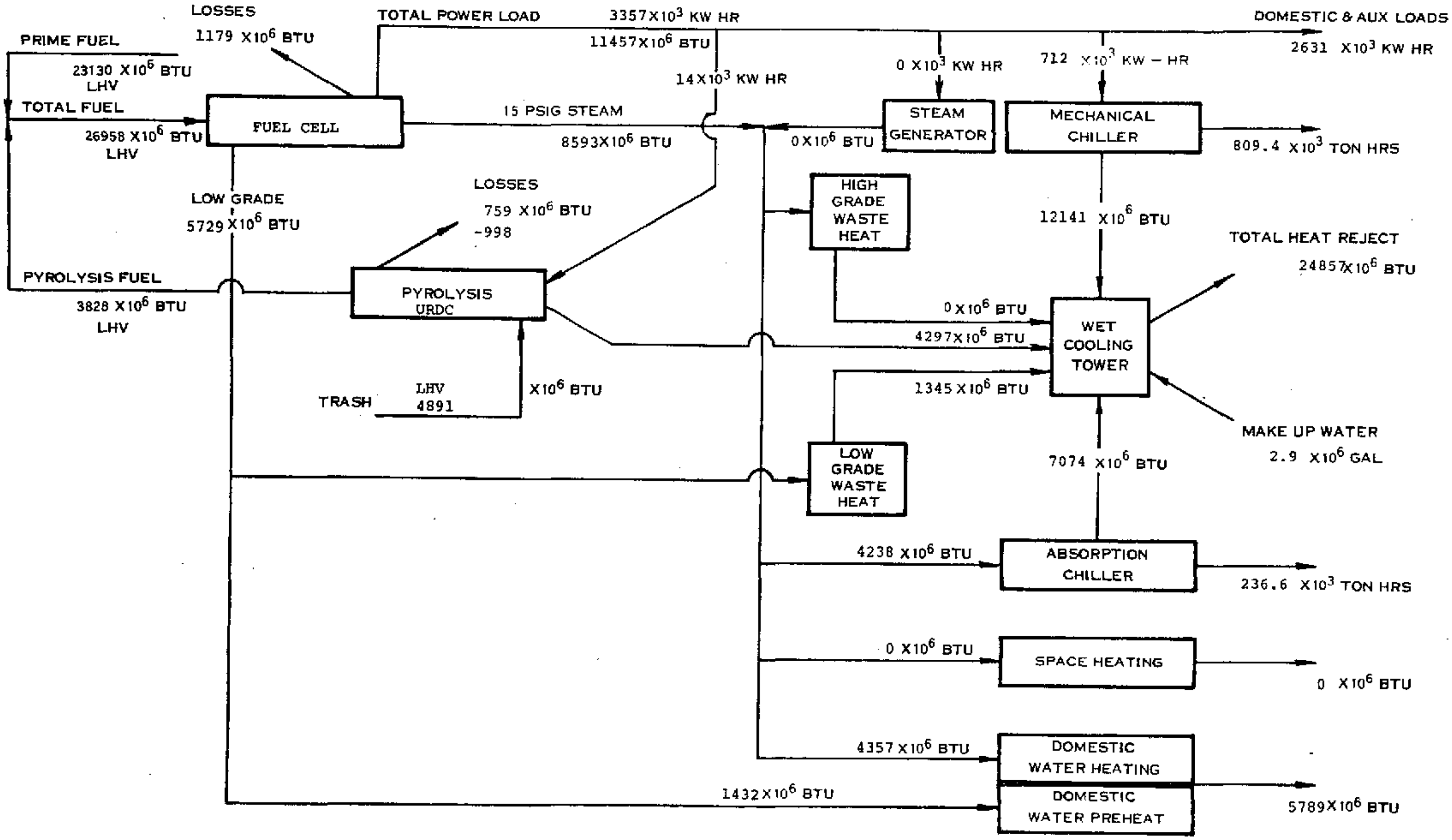
IUS - DIESEL - WINTER
WITH PYROLYSIS (URDC)



IUS - FUEL CELL - ANNUAL
WITH URDC PYROLYSIS

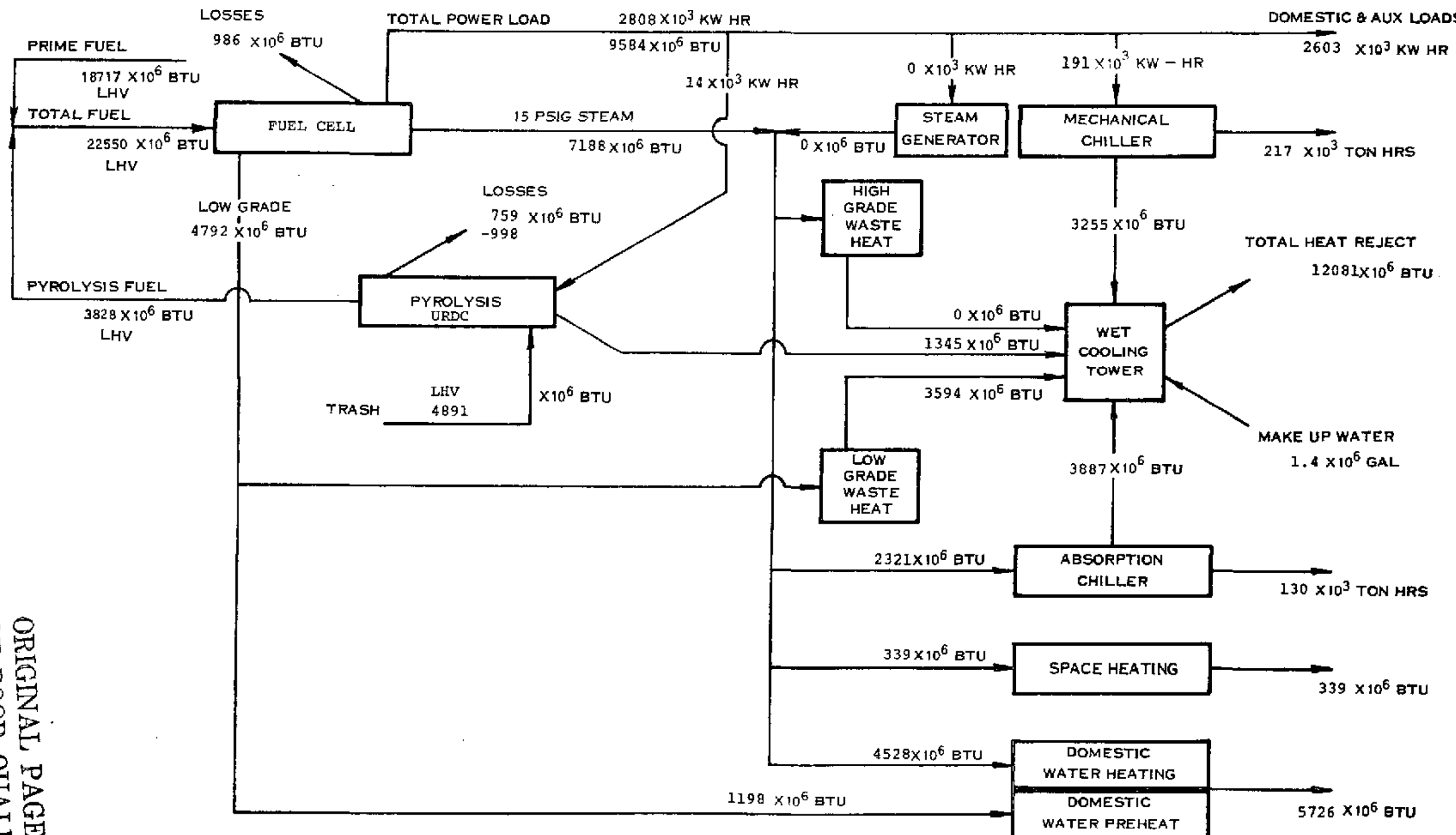


IUS - FUEL CELL - SPRING
WITH URDC PYROLYSIS

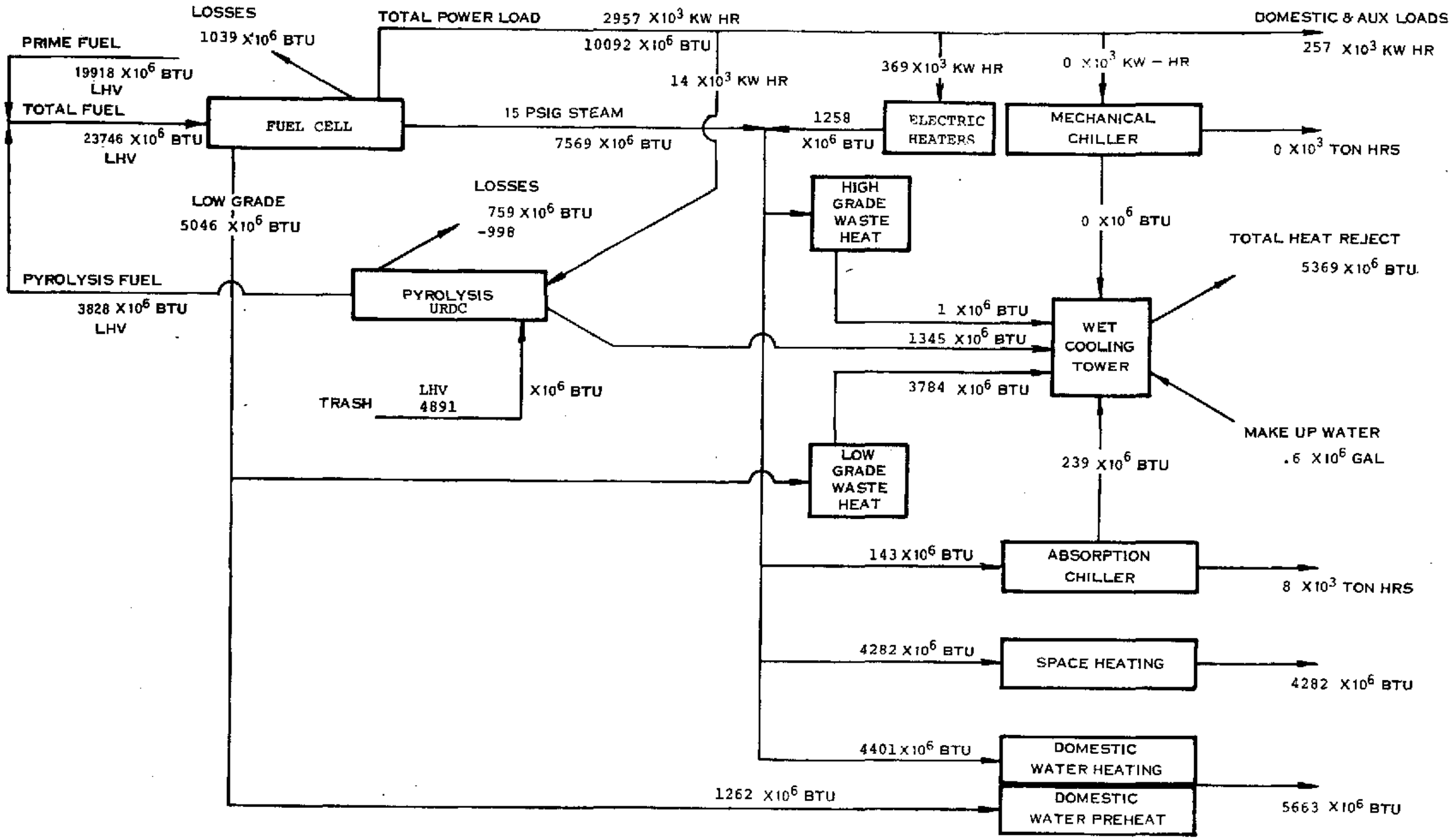


IUS - FUEL CELL - SUMMER

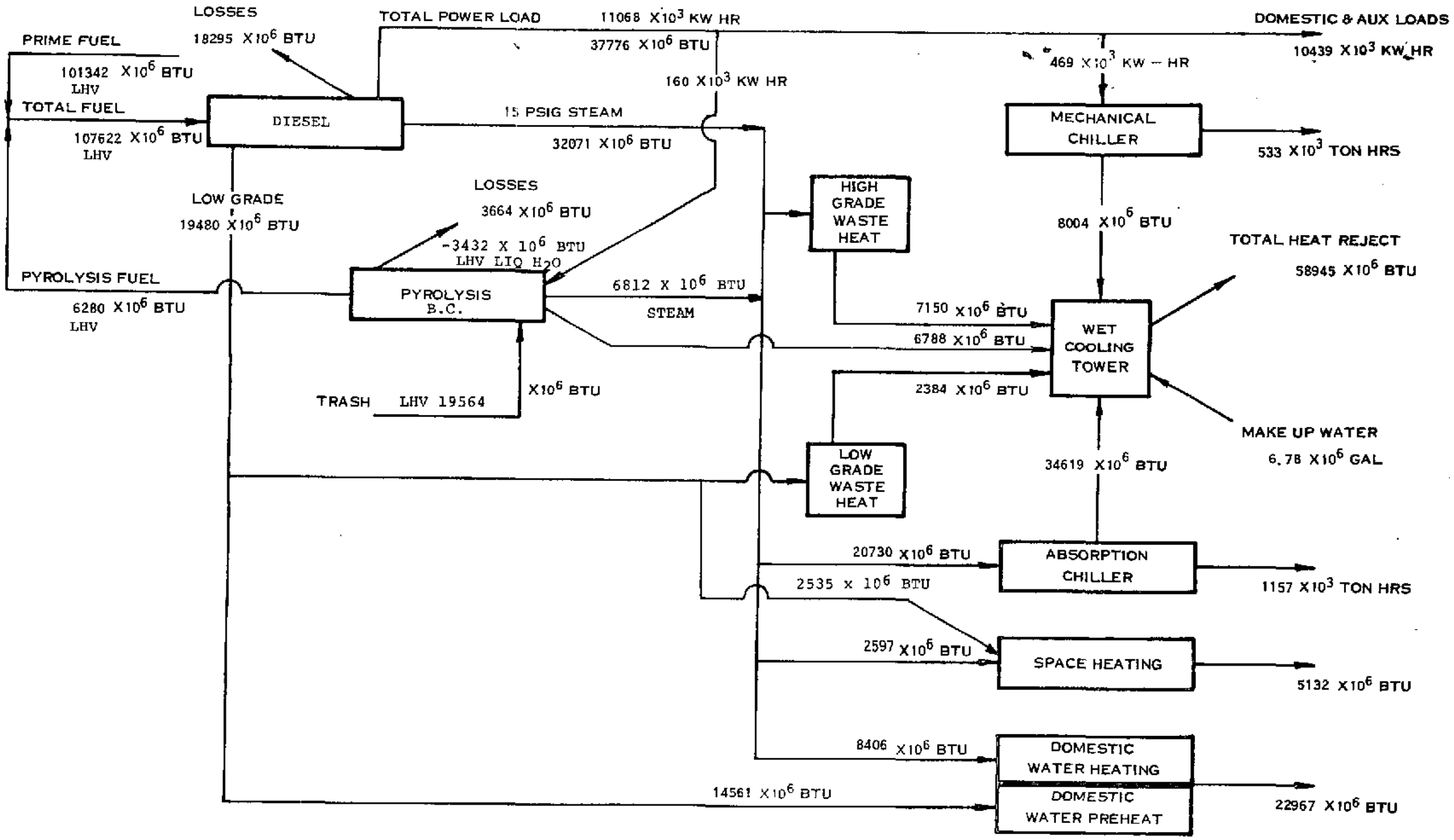
WITH URDC PYROLYSIS



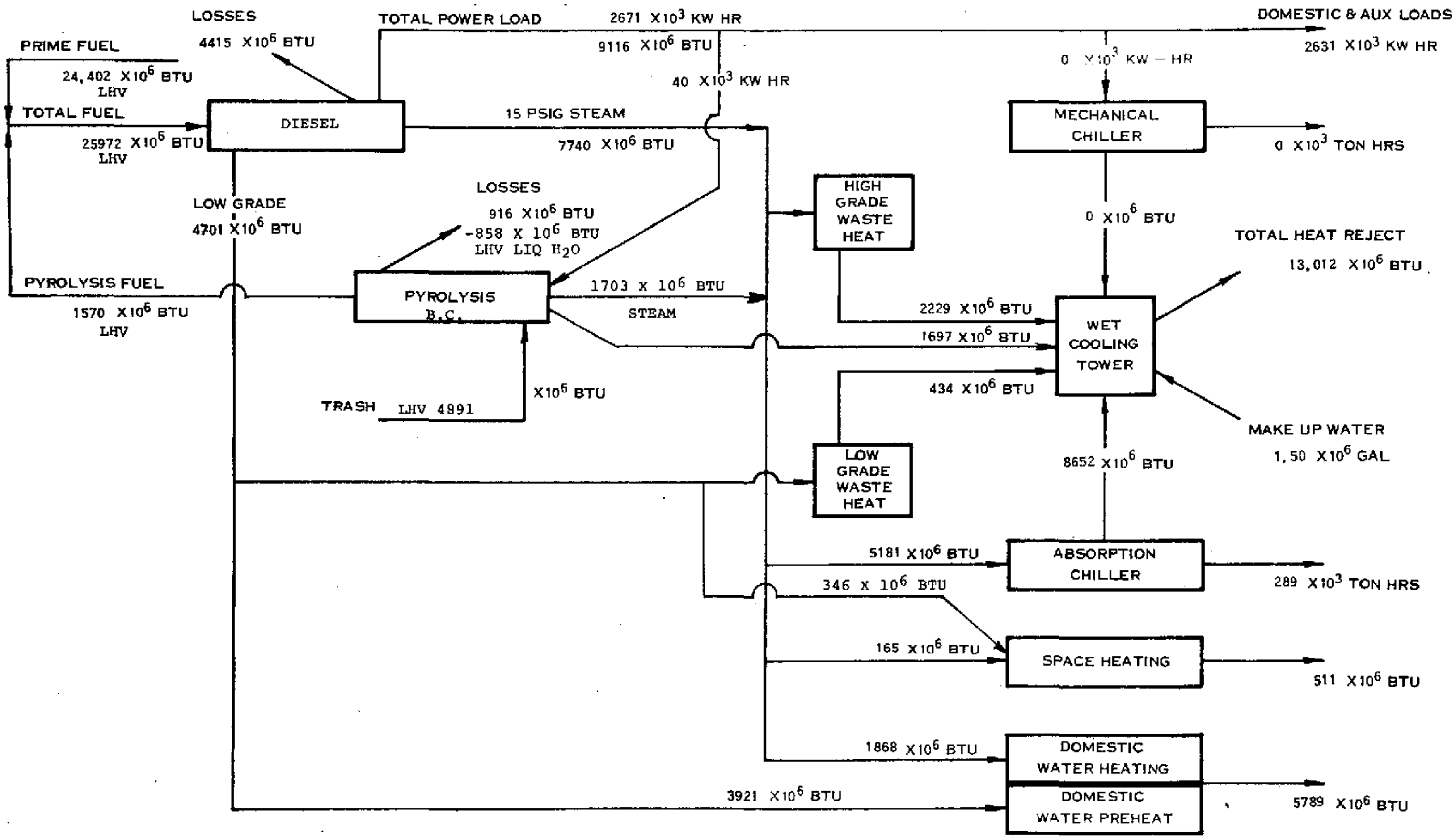
IUS - FUEL CELL - FALL
WITH URDC PYROLYSIS



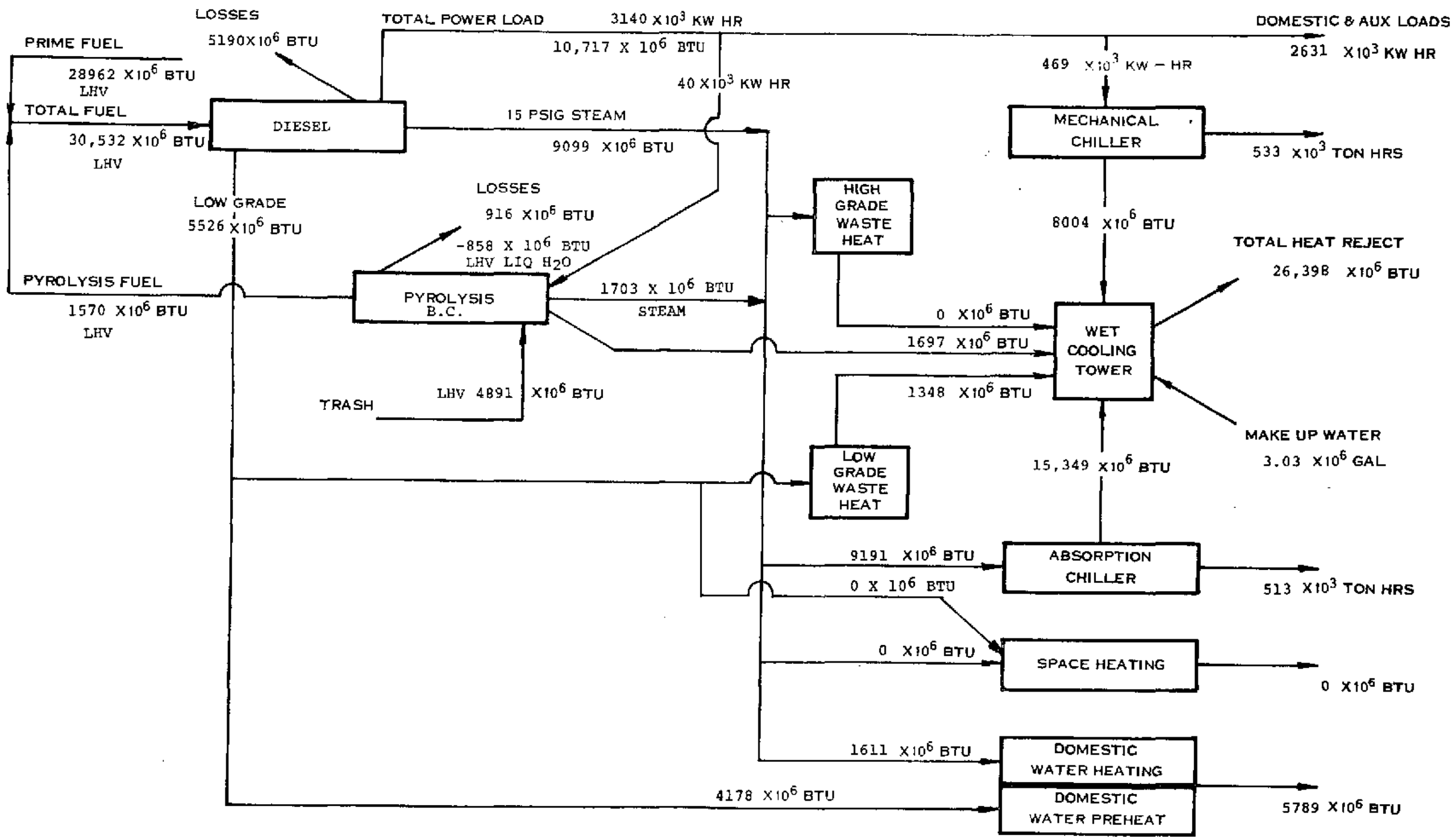
IUS - FUEL CELL - WINTER
WITH URDC PYROLYSIS



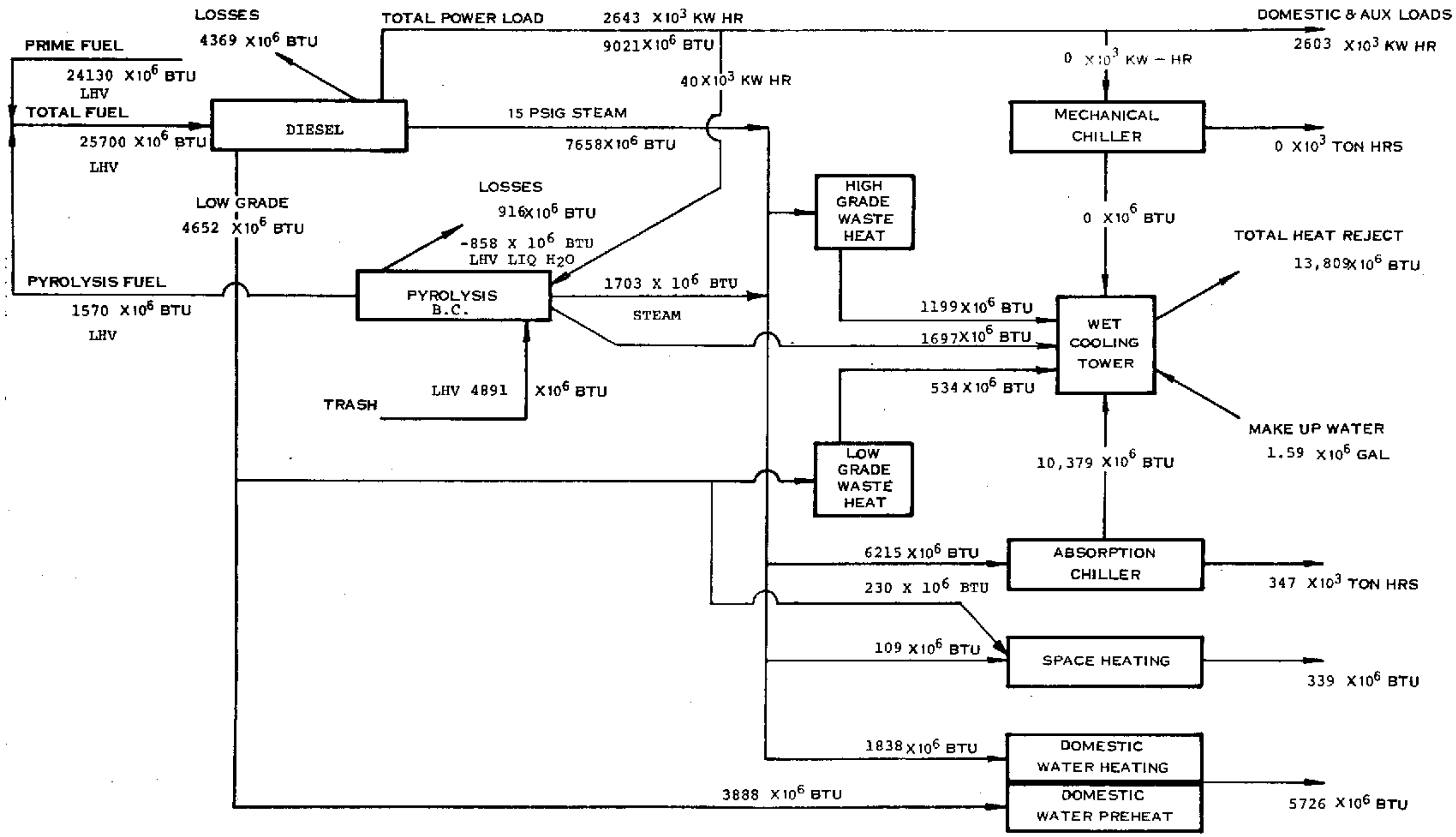
IUS - DIESEL - ANNUAL
WITH PYROLYSIS (B.C.)



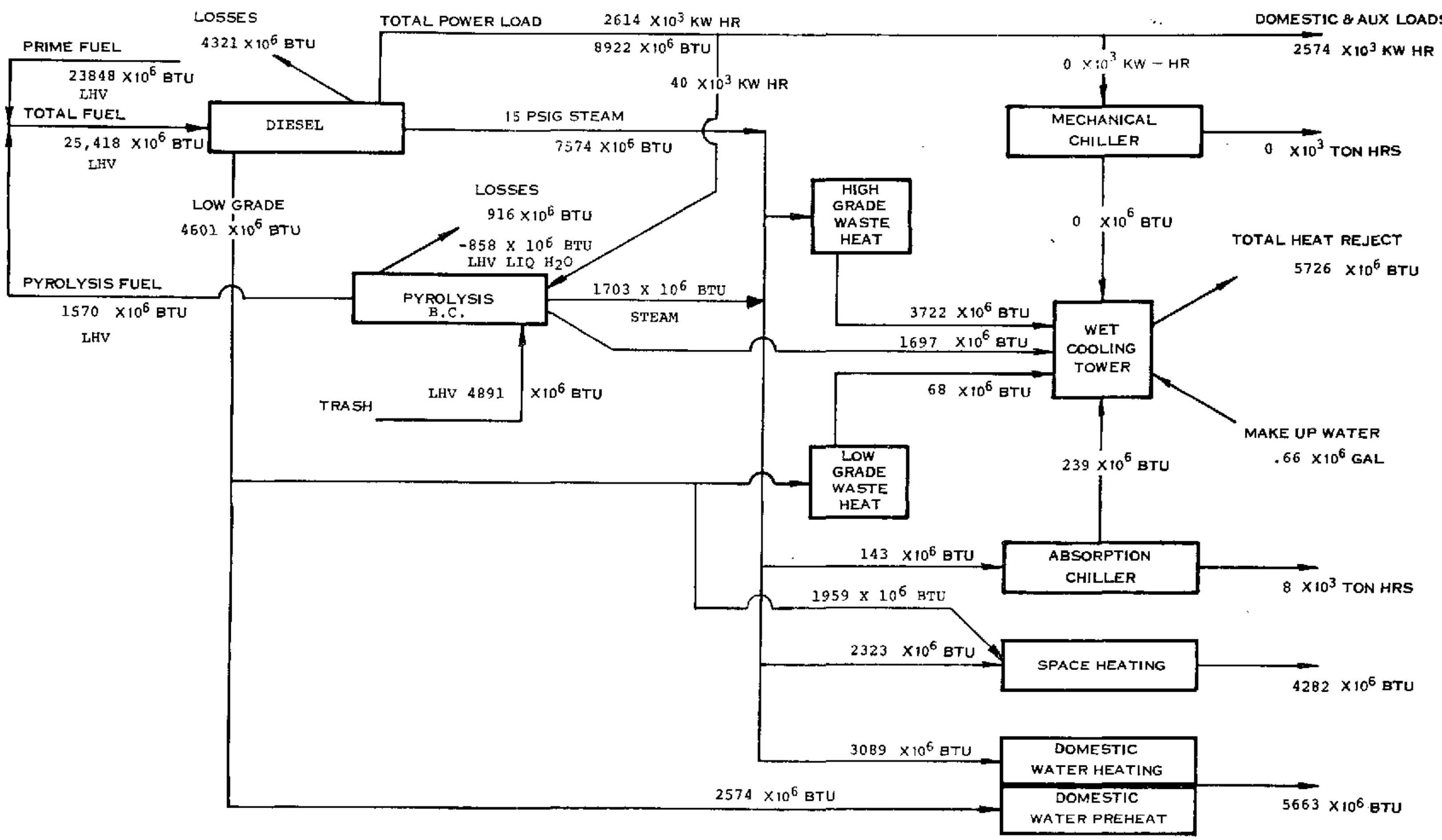
IUS - DIESEL - SPRING
WITH PYROLYSIS (B.C.)



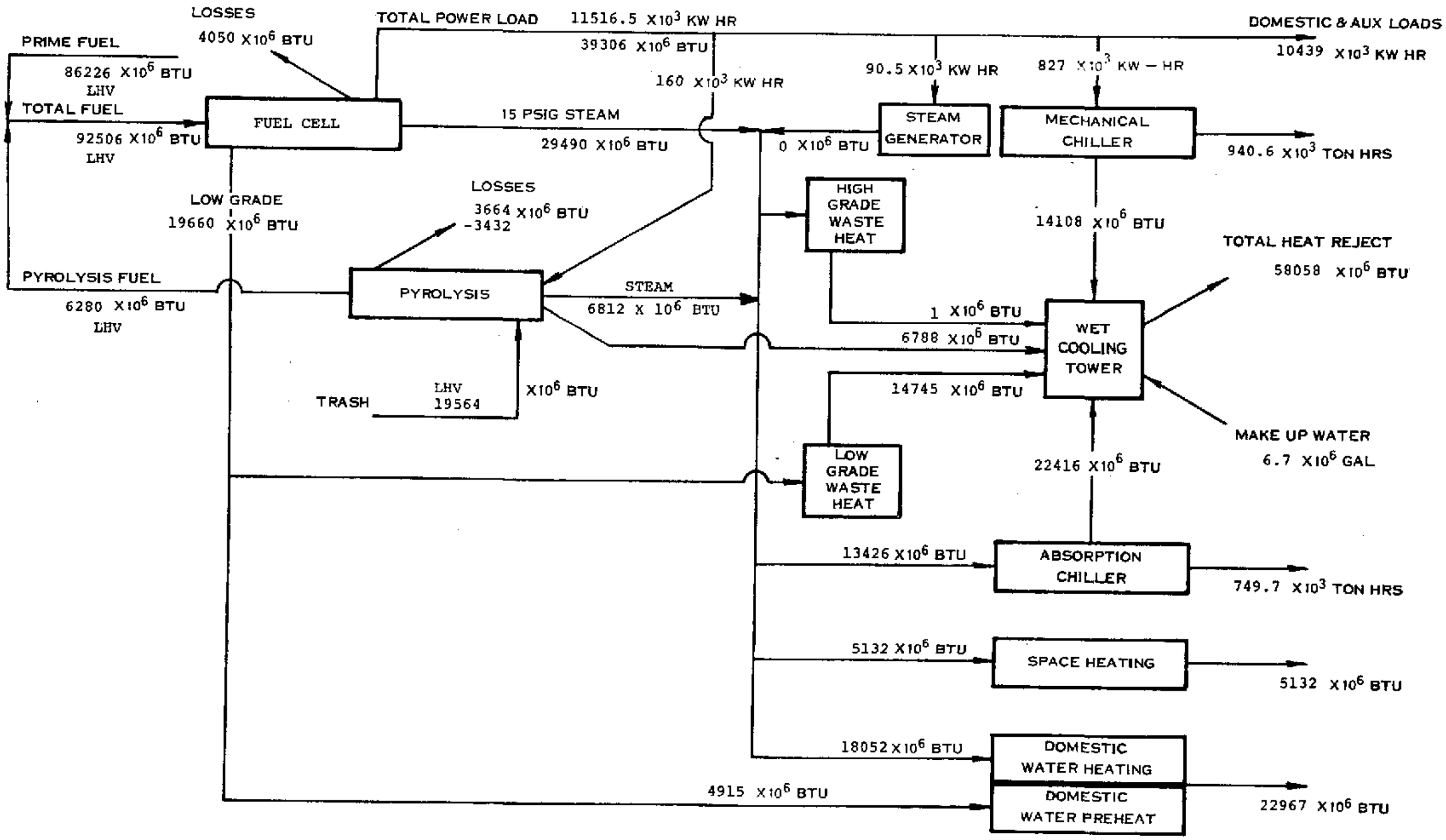
IUS - DIESEL - SUMMER
WITH PYROLYSIS (B.C.)



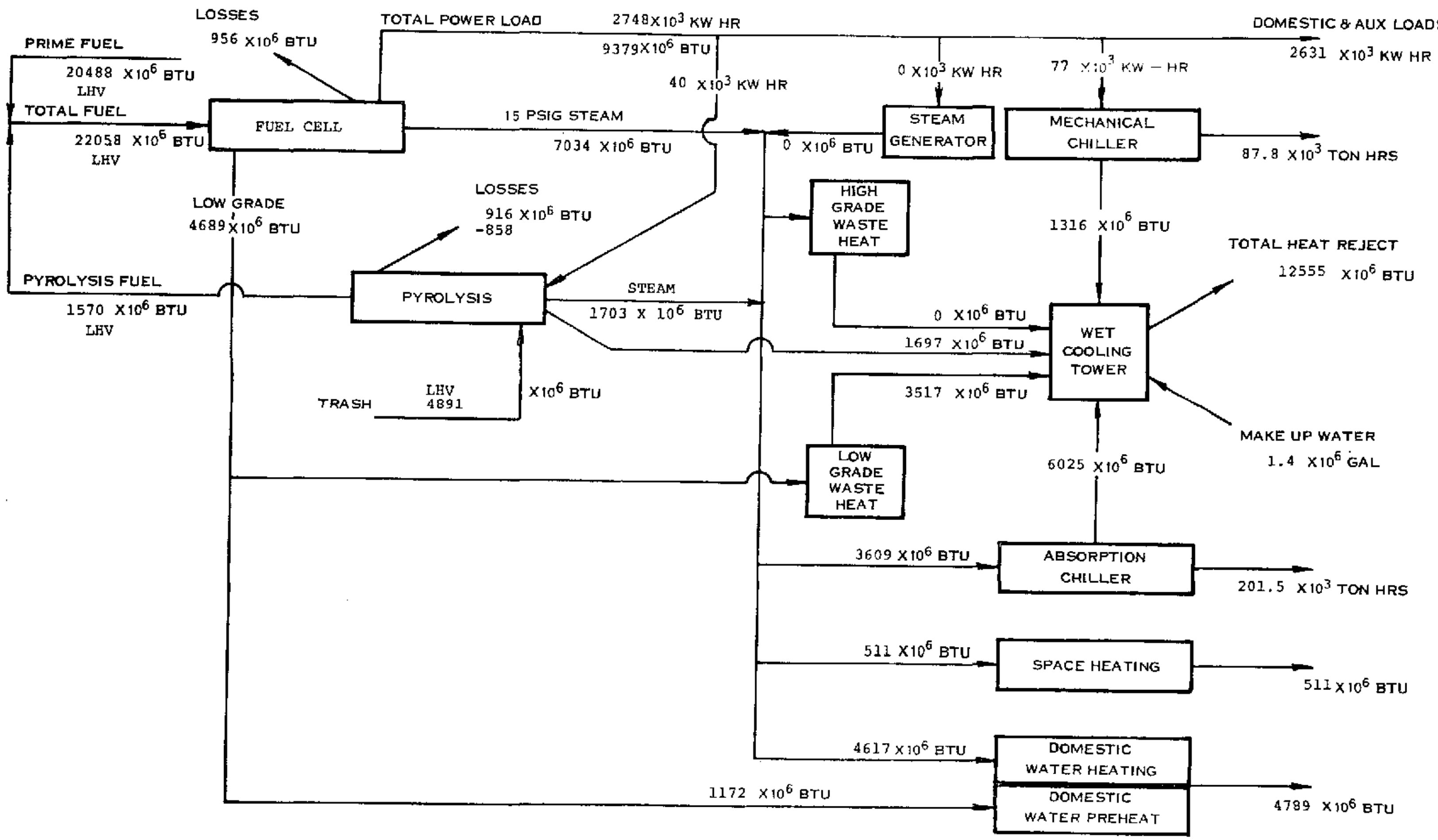
IUS - DIESEL - FALL
WITH PYROLYSIS (B.C.)



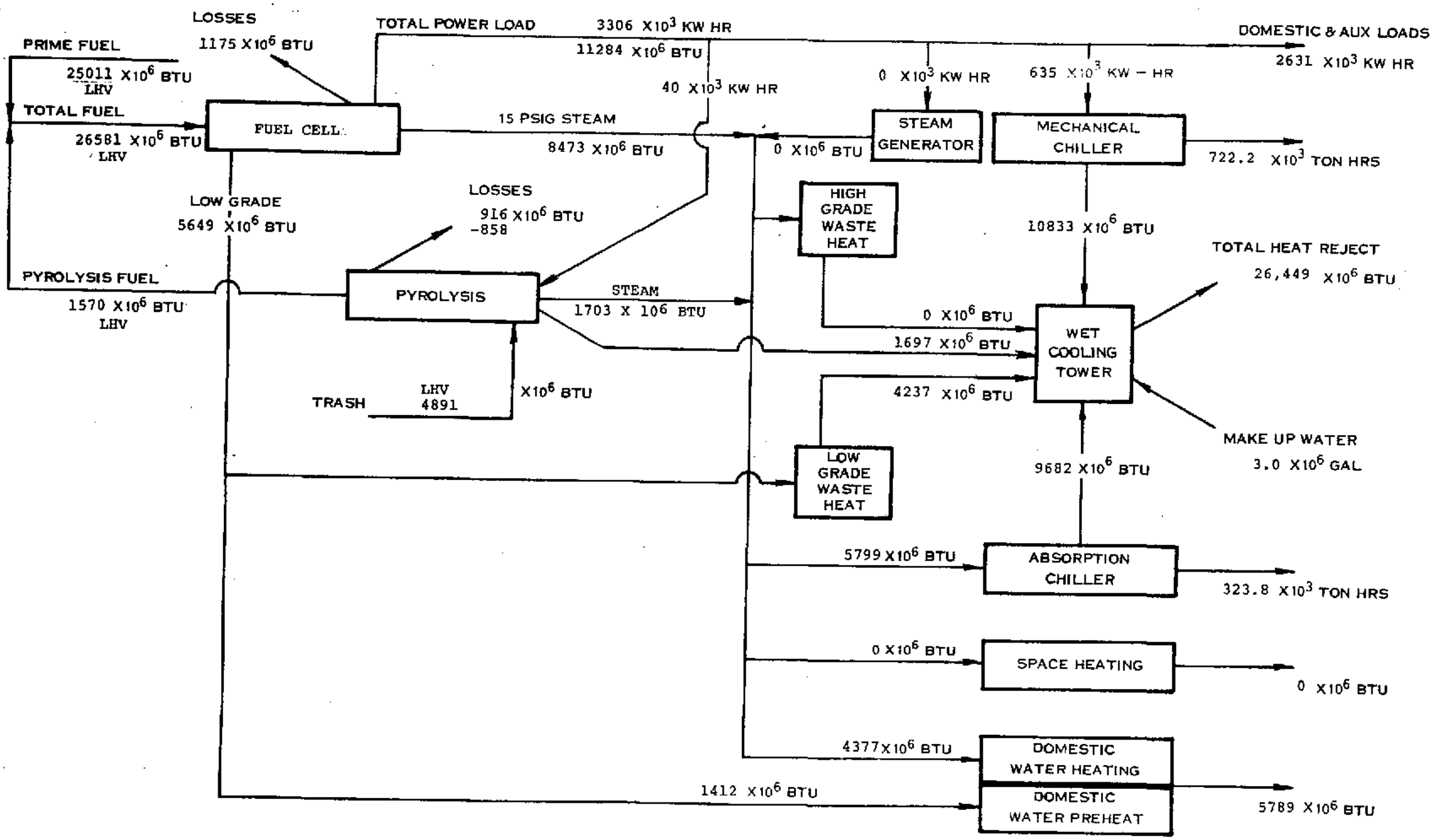
IUS - DIESEL - WINTER
WITH PYROLYSIS (B.C.)



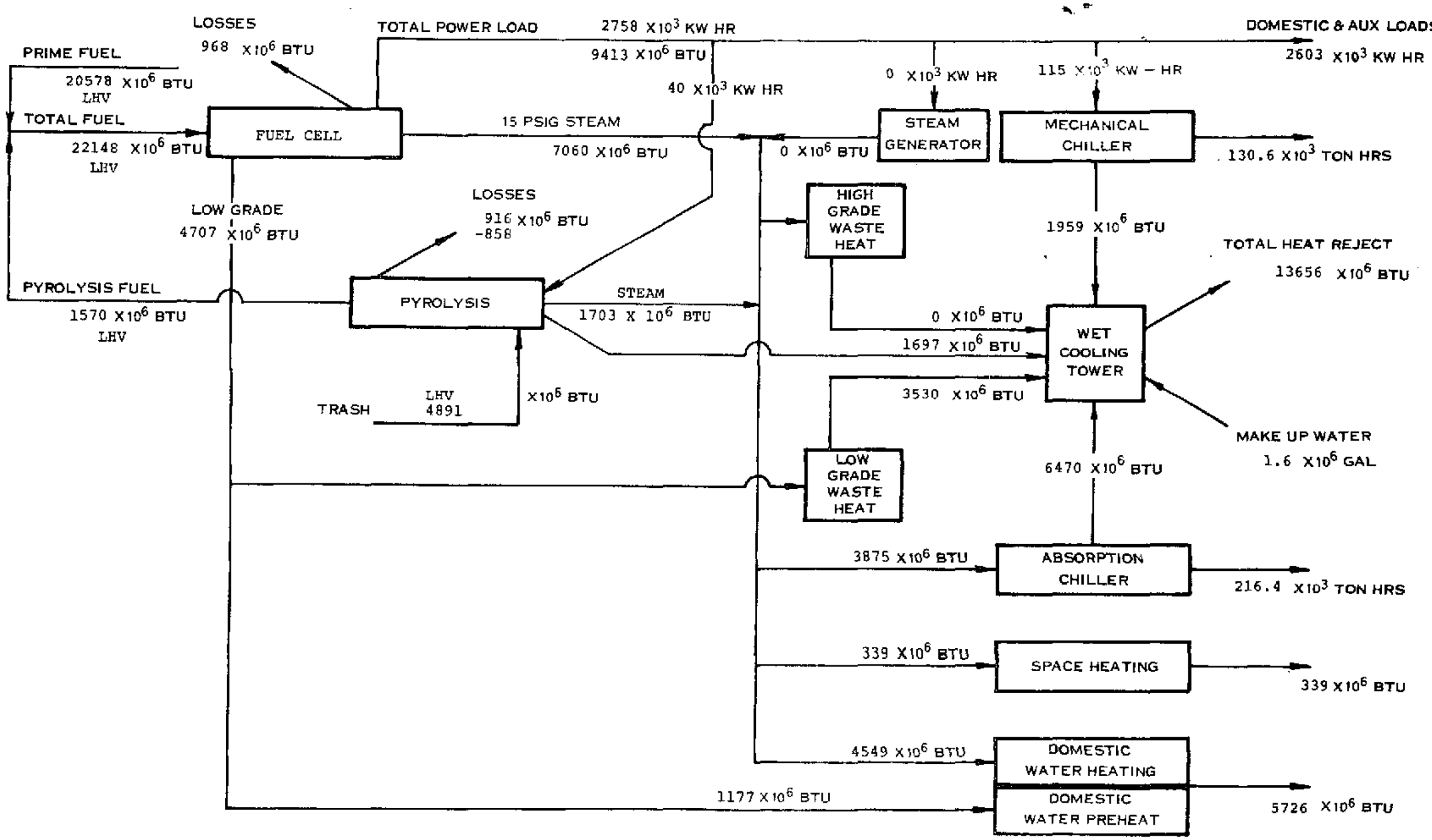
IUS - FUEL CELL - ANNUAL
WITH B. C. PYROLYSIS



IUS - FUEL CELL - SPRING
WITH B. C. PYROLYSIS

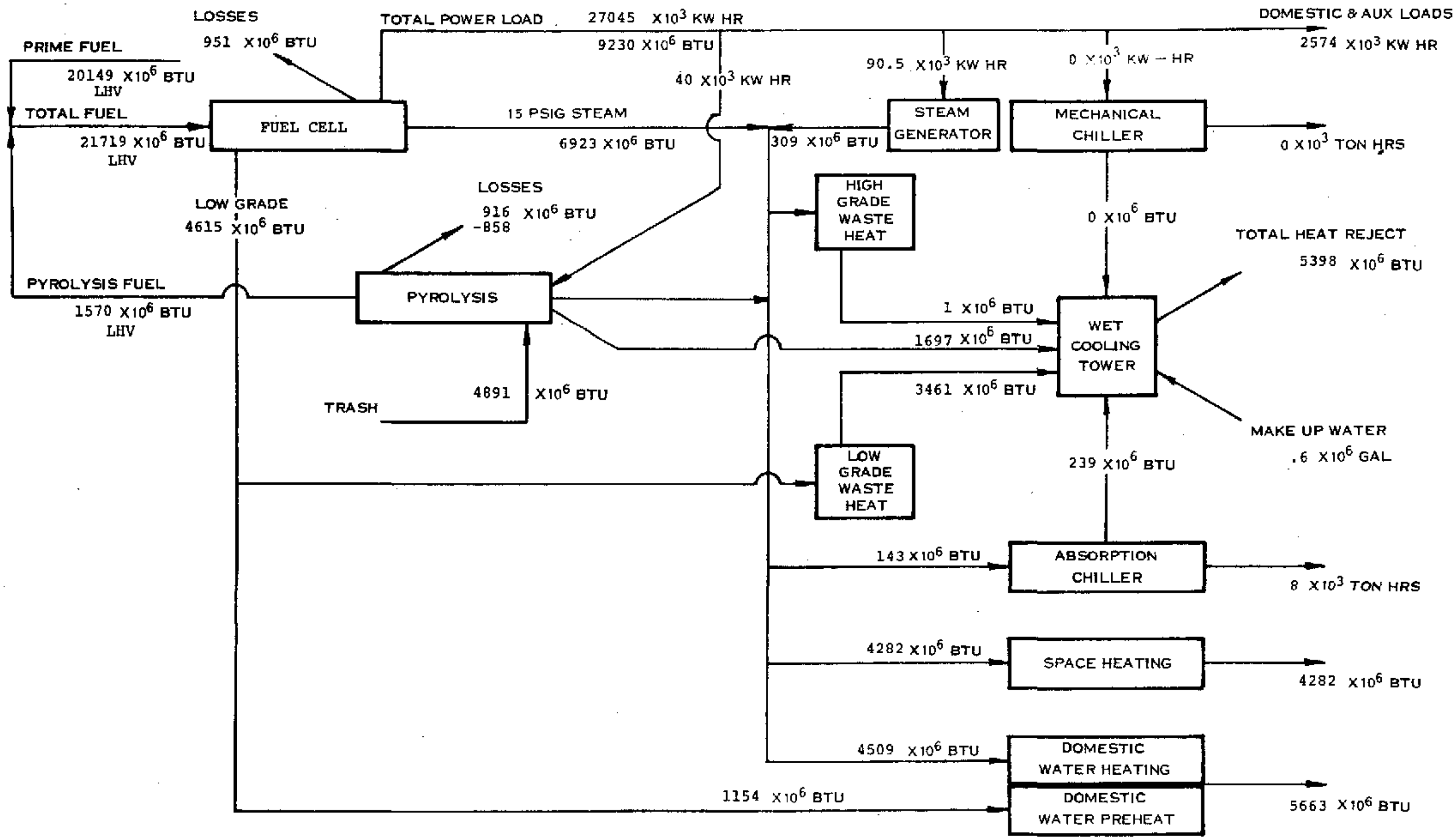


IUS - FUEL CELL - SUMMER
WITH B. C. PYROLYSIS



IUS - FUEL CELL - FALL
WITH B. C. PYROLYSIS

Hamilton Standard
DIVISION OF UNITED AIRCRAFT CORPORATION



IUS - FUEL CELL - WINTER
WITH B. C. PYROLYSIS

APPENDIX E3

PYROLYSIS/IUS ECONOMIC GROUND RULES

E3

PYROLYSIS/IUS ECONOMIC GROUND RULES

The cost analysis for pyrolysis integration into an Integrated Utility System (IUS) will be performed on a delta basis from the Washington 1000 Unit Apartment Complex which was used as a baseline. The baseline IUS has an incineration system for solid waste disposal. In keeping with the primary objectives of this study, emphasis is placed on the details of the pyrolysis installation rather than the IUS.

The baseline IUS to be used for delta cost comparisons will closely resemble the 1000 Unit Apartment Complex in the MIUS Design Study(1). The minor differences between the baseline IUS to be used in this study and the comparable IUS in the Design Study Report(1) are the result of the simplifying assumptions made in the performance analysis model and some of the technical ground rules established at the outset of the pyrolysis study program. No attempt will be made to adjust the total IUS cost level for these minor differences. The resultant cost differences between the baseline IUS with incineration and an IUS with pyrolysis will be based on the major differences of the solid waste systems and will be representative of any 1000 Unit Apartment Complex IUS.

The impact of integrating pyrolysis into an IUS is expected to be negligible on the water management system and IUS building costs. The pyrolysis requires approximately 1000 GPD of treated waste water and returns about 30 percent more for treatment. The waste water treatment plant processes approximately 85,000 GPD. It has been indicated by the NASA that the residuals returned to the waste water treatment plant will not impact that system. It is assumed that the building requirements will be equivalent for either pyrolysis or incineration. In general, both systems will require structure or shelters separated from the remaining IUS equipment.

The economic ground rules and supporting rationale for each subsystem are discussed in the following sections. Wherever feasible, cost analysis information have been taken from the MIUS Design Study Report(1). Fuel will be treated as a separate item in the analysis since it is expected to be the focus of the most significant cost impact. Fuel consumption will be estimated from the annual flow charts for each IUS configuration being considered.

Twenty year cost will be the sum of the initial investment plus the Operating and Maintenance (O&M) costs for the twenty year period. The twenty year O&M will be estimated by escalating and discounting the 1974 (first year) O&M as agreed to with the NASA earlier in the study.

Using this procedure, fuel is escalated at 10% per year and all other O&M at 5% per year. The discount rate is 15% on all O&M. The twenty year costs of fuel is the first year fuel costs multiplied by 12.95; the twenty year costs of all other O&M is the first year cost multiplied by 8.80. The derivation of these factors was described in an earlier submittal to the NASA and presented at the review meeting October 30, 1974.

Solid Waste Subsystems

The cost variations of the solid waste subsystems to be considered will include the initial, annual operating and maintenance cost of the system itself as described below. The impact of solid waste systems' variations on equipment sizing in other subsystems (e.g., electrical power generation and HVAC) are assessed as costs to the subsystem affected, not the solid waste system causing it. This approach is taken because it is the twenty year cost of an IUS with the various solid waste systems which are to be compared.

Duty cycles for all solid waste systems will be as follows:

1. 24 Hours/Day, 6 Days/Week
2. 8 Hours/Day, 7 Days/Week

Pyrolysis

Pyrolysis system costs will be generated based on vendor inquiries and budgetary estimates made during the course of

preliminary design activities. In addition to the component purchase costs, the following estimates will be included as applicable:

1. Installation Labor
2. Site Prep(3)

Reactor and Hx	3% of Component Cost

3. Specialized Maintenance

Reactor Rebricking	20% of Initial Component Every 3 Years
Misc. Reactor Materials(3)	1% Per Year
Air Preheaters(3)	10% Per Year
Other Components(3)	3% Per Year

Incinerator

The detail incinerator system costs will be taken directly from the MIUS Design Study Report(1). Adjustments of the system costs will be made for various duty cycles and other use variations as required.

IUS Without Solid Waste Disposal

An IUS without any provision for solid waste disposal will be considered as agreed to with the NASA. In this case, all costs associated with the incineration system will be deleted. The waste collection cart system costs were retained in the IUS and are not considered part of the disposal system. Landfill costs will not be considered for this system.

Electrical Power Generation

Electrical power generating costs will be based on the information in the MIUS Design Study. Variation in capital costs will be calculated at $195/KW installed capacity for both diesel generators[1] and fuel cells. The application of this cost rate to fuel cell systems is based on the assumption that they must be competitive with diesel generator systems in order to be marketable. No firm cost projections for fuel cells were available for this study. While there are several factors such as electrical conversion efficiency, maintenance costs, and usable high grade heat production which may allow slightly higher fuel cell capital costs to be competitive in an overall sense, it is felt that any attempt to take these into account at this time would be beyond the scope of the pyrolysis study. In general, the equating of diesel generator costs to fuel cell costs will provide reasonably reliable cost comparisons between a fuel cell IUS installation with the various solid waste systems.

The installed electrical generating capacity will be sized for meeting the peak load (domestic plus cooling) on a design summer day given in the MIUS Design Study Report when high grade heat is unavilable from the solid waste system (solid waste system down due to schedule or repair, etc.). This peak load depends on the split between compression chilling and absorption chilling and for each IUS considered, this split will be selected

based on overall 20 year system costs. Further discussion of this split may be found in the section on HVAC. The load will be carried on three engines with a fourth available for maintenance. The four engines will be assumed identical except for possible incorporation of engines with added complexity for the pyrolysis gases. It is anticipated that such engines would be similar to the present day dual fuel engines.

The utilization of pyrolysis fuel gases in oil fired diesel generators is anticipated to require engines similar to dual fuel engines. It will be assumed that when pyrolysis is integrated into the IUS, two of the four engines will have this capability. The added cost of the dual fuel capability in the Fairbanks-Morse 38D 8 1/8 engine generator in the size range being considered here is approximately \$15,000/engine(4) on the initial cost. Additional annual maintenance costs for the dual fuel engine is assessed at 5.8%(5) applied to the delta.

Fuel

Fuel costs will be calculated at \$1.85/million Btu on a LHV basis as established early in the Pyrolysis System Evaluation Study Program.

Heating Ventilating and Air Conditioning

It will be assumed that the air conditioning equipment must be sized to provide cooling for the peak load on a design summer day for both normal operating conditions, i.e., when the solid

waste system is generating high grade waste heat for the absorption chillers and when the solid waste system is not operating, i.e., no solid waste high grade heat for absorption chilling. The absorption chillers will be sized to utilize 100% of the steam generated at the peak cooling condition.

The cost of size variations on the chillers will be evaluated at:

Absorption Chillers	\$115/Ton	See (2)
Compression Chillers	\$104/Ton	

The annual maintenance cost on the chilling equipment will be assessed at 3.5%[2] applied to the delta. As discussed earlier, the cooling equipment sizing must be done with the electrical generating equipment at the IUS level on 20 year costs for each system configuration. Supplementary steam generation will be considered for the case of no solid waste system operation. No cost variations will be included for the cooling tower loads because the sizing based on summer cooling requirements are expected to be negligible.

Control/Monitoring System

The cost of control and monitoring equipment for the baseline MIUS is not effected by the incorporation of pyrolysis. The controls and instrumentation required for the pyrolysis subsystem are included in the costs of the subsystem.

System Operating Crew

The solid waste system operating on an eight hour/day, seven day/week duty cycle will not require additional manpower over the baseline system requirement which has two shift coverage. However, operating 24 hours/day for six days per week will require an additional two semi-skilled employees for third shift operation. This is estimated[1] on the same basis as the IUS baseline as indicated below.

6 Days/Week

Two Semi-Skilled Employees x 6/5	$27,360
Overtime (100 Hours Each, 2 Men)	1,650
	$29,010

No attempt will be made to adjust shift schedules for the IUS as it is considered beyond the scope of this study.

NOTES

(1) MIUS Design Study Report

(2) MIUS Design Study Report, Table 5.1-6A

(3) Engineering estimates based on components of equivalent complexity and/or size in the MIUS Design Study Report.

(4) Telecon with Fairbanks-Morse.

(5) From MIUS Design Study Report
$23,100 ÷ 396,710 x 100 = 5.8%
Table 5.1-1

APPENDIX E4

TWENTY YEAR COST CALCULATION PROCEDURE

E4

TWENTY YEAR COST CALCULATION PROCEDURE

The following calculation procedures were used to make total 20 year cost comparisons on a bsis that was consistent with the study groundrules and the NASA's "Preliminary Design Study of a Baseline MIUS System".

1. Differential capital costs were estimated assuming mid-1974 construction in Washington, D. C.
2. Differential operating costs were estimated again assuming the system was operated in Washington, D. C. in mid-1974. A fuel oil cost of $\$1.75/10^6$ BTU HHV (Equivalent to $\$1.85/10^6$ BTU/LHV) was used.
3. The present (mid-1974) value of the total fuel outly for the 20 year period was calculated. Since fuel cost is assumed to escalate 10% per year due to inflation, while the discount rate is 15%, the present value can be calculated using normal interest tables or formulas with an effective rate of 4.55%. (See Attachment for details.) The present worth factor is 12.95, and the total fuel cost is equal to 12.95 x 1974 fuel cost.
4. The present value of the remaining operation and maintenance costs for the total 20 year period was calculated. At a 15% discount rate and 5% escalation, the effective discount rate is 9.52%. The present worth factor is 8.80, and the total O&M cost is 8.80 x 1974 cost.

5. The total 20 year cost then is the sum of the capital cost plus the 20 year discounted and escalated fuel cost plus the remaining 20 year discounted and escalated O&M costs.

This approach appears to be consistent with the NASA's calculation. To improve on this approach would require a number of detailed assumptions on the financial approach of the developer and, therefore, would have to be much more situation specific, i.e., it is impossible to make a really meaningful financial comparison of alternatives except in terms of a specific and well defined financial structure.

ATTACHMENT

If C represents an initial yearly cost which is constant except for inflation which occurs at a constant rate of e% per year, then the yearly costs in the year that they are incurred will be:

$$C\ (1 + e)$$
$$C\ (1 + e)^2$$
$$C\ (1 + e)^n$$

A competing effect is the time value of money - i.e., a sum of money. S presently in hand will have a value in following years of:

$$S\ (1 + d)$$
$$S\ (1 + d)^2$$
$$S\ (1 + d)^n$$

where d is the discount or interest rate. The ratio of the present value of the sum to its value n years from now is equal to:

$$\frac{1}{(1 + d)^n}$$

The present value of the escalating fuel cost then becomes:

$$C \frac{(1 + e)}{(1 + d)}$$

$$C \frac{(1 + e)^2}{(1 + d)}$$

$$C \frac{(1 + e)^n}{(1 + d)}$$

The present value of a constant yearly expense is:

$$\frac{E}{1 + d}$$

$$\frac{E}{(1 + d)^2}$$

$$\frac{E}{(1 + d)^n}$$

Comparing the two sets shows that the escalated and discounted case can be treated as a simple present value calculation assuming a constant cost equal to the initial cost and an effective discount rate, d_{eff}, defined as follows:

$$\frac{1 + e}{1 + d} = \frac{1}{1 + d_{eff}}$$

$$d_{eff} = \frac{d - e}{1 + e}$$

For fuel the discount rate is equal to 15%, and the fuel escalation is 10% per year, **while for the remaining O&M cost, the** inflation factor is 5%. The effective interest rate then becomes:

$$d_{eff} = 4.55\% \text{ (fuels)}$$

$$d_{eff} = 9.52\% \text{ (remaining O\&M costs)}$$

The present worth factor (PWF) is defined such that the present value of a series of constant expenses is equal to the single yearly expense times PWF. PWF is a function of the discount rate (i) and the number of years (n) that payments have to be made. It can be obtained from usual interest tables or calculated directly as follows:

$$PWF = \frac{(1 + i)^n - 1}{i(1 + i)^n}$$

Substituting the appropriate values gives us:

$$PWF = 12.95 \text{ (fuels)}$$

$$PWF = 8.80 \text{ (remaining O\&M costs)}$$

The total 20 year escalated and discounted costs then can be calculated as follows:

Total 20 year cost = capital cost + 12.95 x initial year's fuel cost + 8.80 **x initial** year's O&M cost

This can be compared to results shown on page 6-46 of Preliminary Design Study of a Base Line MIUS System as follows:

$$\text{yearly fuel cost} = \frac{4{,}288{,}000}{20} = 214{,}400$$

$$\text{yearly O\&M} = \frac{4{,}411{,}000}{20} = 220{,}600$$

The total cost for the 10% fuel escalation 5% other escalation case can be calculated and compared to the cost tables given in the MIUS report as follows:

capital	= 2,708,000
fuel = 214,400 x 12.95	= 2,776,000
O&M = 220,600 x 8.80	= 1,941,000
	$7,425,000 versus $7,426,000

For the straight 5% escalation case the comparison becomes:

capital	= 2,708,000
fuel = 214,400 x 8.80	= 1,887,000
O&M = 220,600 x 8.80	= 1,941,000
	$6,536,000 versus $6,534,000

The difference appears to be well within the expected computational tolerance.

APPENDIX E5

INTEGRATED PYROLYSIS/IUS ECONOMIC EVALUATION

E5

INTEGRATION PYROLYSIS/IUS ECONOMIC EVALUATION

The economic evaluation of the pyrolysis systems integrated into the baseline IUS was made along with an integrated incineration/IUS system for comparison. The evaluation was performed in accordance with Appendix E3 with both diesel generators and fuel cells for the IUS electrical power generating subsystem, and with the waste disposal subsystem operating on two different duty cycles 24 hours/day for 6 days/week and 8 hours/day for 7 days/week. The integrated IUS results are summarized in Tables 1 and 2. The cost values represent a delta from an IUS with no waste disposal provisions or costs beyond collection within the apartment complex. Tables 3 through 6 present the results at the subsystem level.

All cost delta information is based on mid 1974 dollars for capital and annual O&M. Twenty year costs are calculated by applying a 12.95 factor on fuel and an 8.8 factor on all other O&M. Derivation of these factors may be found in Appendix E4. They were based on escalations of 10 percent/year for fuel, 5 percent/year for all other O&M, and uniformly discounted at 15 percent/year.

PYROLYSIS SYSTEMS COSTS

The capital costs of the pyrolysis systems were based on the results of Appendices B4 and C4 for URDC and Barber-Colman, respectively, operating for 24 hours/day, 6 days/week. The

TABLE 1

COST DELTA SUMMARY - DIESEL IUS

		Incinerator	URDC Pyrolysis	Barber-Colman Pyrolysis
8 Hour/Day, 7 Days/Week	Capital	149.2	231.5	347.0
	Annual O&M	19.7	-19.7	-.3
	20 Year O&M	189.3	-284.0	-45.9
	20 Year Cost	338.5	-52.5	301.1
24 Hours/Day, 6 Days/Week	Capital	63.5	150.9	239.8
	Annual O&M	43.5	7.7	26.1
	20 Year O&M	421.9	-44.9	186.9
	20 Year Cost	485.4	106.0	426.7

TABLE 2

COST DELTA SUMMARY - FUEL CELL IUS

		Incinerator	URDC Pyrolysis	Barber-Colman Pyrolysis
8 Hour/Day, 7 Days/Week	Capital	149.7	201.4	316.2
	Annual O&M	9.9	-21.7	8.4
	20 Year O&M	62.8	-302.6	-142.8
	20 Year Cost	212.5	-101.2	173.4
24 Hour/Day, 6 Days/Week	Capital	64.0	133.6	209.0
	Annual O&M	33.8	5.7	18.1
	20 Year O&M	268.9	-63.5	89.8
	20 Year Cost	332.9	70.0	298.8

TABLE 3
DELTA COST - IUS WITH DIESEL GENERATORS
SOLID WASTE OPERATION 8 HOUR/DAY, 7 DAYS/WEEK

	Incineration	URDC	Barber-Colman
Capital ($1,000's)			
Solid Waste	+ 172.5	+ 200.0	+ 320.0
Electrical Power (Diesel)	- 24.6	+ 31.5	+ 26.3
Absorption Chillers	+ 12.8	0	+ 5.6
Compression Chillers	- 11.5	0	- 4.9
Total	+ 149.2	+ 231.5	+ 347.0
Annual O&M ($)			
Solid Waste	+15,687	+ 5,225	+ 8,280
Electrical Power (Diesel)	0	+ 1,740	+ 1,740
Operating Crew	0	0	0
Subtotal	+15,687	+ 6,965	+10,020
Fuel	+ 3,965	-26,663	-10,337
Total O&M	+19,652	-19,698	- 317
20 Year Costs ($1,000's)			
20 Year Fuel	+ 51.3	- 345.3	- 133.9
20 Year Other O&M	+ 138.0	+ 61.3	+ 88.0
Total 20 Year O&M	+ 189.3	- 284.0	- 45.9
Capital	+ 149.2	+ 231.5	+ 347.0
Total 20 Year Cost	+ 338.5	- 52.5	+ 301.1

TABLE 4
DELTA COST - IUS WITH DIESEL GENERATORS
SOLID WASTE OPERATION 24 HOUR/DAY, 6 DAYS/WEEK

	Incineration	URDC	Barber-Colman
Capital ($1,000's)			
Solid Waste	+ 86.8	+ 132.2	+ 212.8
Electrical Power (Diesel)	- 24.6	+ 31.5	+ 26.3
Absorption Chillers	+ 12.8	0	+ 5.6
Compression Chillers	- 11.5	0	- 4.9
Total	+ 63.5	+ 150.9	+ 239.8
Annual O&M ($)			
Solid Waste	+ 11,506	+ 4,000	+ 5,865
Electrical Power (Diesel)	0	+ 1,740	+ 1,740
Operating Crew	+ 29,010	+ 29,010	+ 29,010
Subtotal	+ 40,516	+ 34,750	+ 36,615
Fuel	+ 3,006	- 27,082	- 10,447
Total	+ 43,522	+ 7,668	+ 26,168
20 Year Costs ($1,000's)			
20 Year Fuel	+ 38.9	- 350.7	- 135.3
20 Year Other O&M	+ 383.0	+ 305.8	+ 322.2
Total 20 Year O&M	+ 421.9	- 44.9	+ 186.9
Capital	+ 63.5	+ 150.9	+ 239.8
Total 20 Year Cost	+ 485.4	+ 106.0	+ 426.7

TABLE 5
DELTA COST - IUS WITH FUEL CELLS
SOLID WASTE OPERATION 8 HOUR/DAY, 7 DAYS/WEEK

	Incineration	URDC	Barber-Colman
Capital ($1,000's)			
Solid Waste	+ 172.5	+ 200.0	+ 320.0
Electrical Power (Fuel Cell)	- 24.1	+ 1.4	- 4.3
Absorption Chillers	+ 12.8	+ .1	+ 5.5
Compression Chillers	- 11.5	- .1	- 5.0
Total Capital	+ 149.7	+ 201.4	+ 316.2
Annual O&M ($)			
Solid Waste	+15,687	+ 5,225	+ 8,280
Electrical Power (Fuel Cell)	0	0	0
Operating Crew	0	0	0
Subtotal O&M	+15,687	+ 5,225	+ 8,280
Fuel	- 5,807	-26,921	-16,654
Total O&M	+ 9,880	-21,696	- 8,374
20 Year Costs ($1,000's)			
20 Year Fuel	- 75.2	- 348.6	- 215.7
20 Year Other O&M	+ 138.0	+ 46.0	+ 72.9
Total 20 Year O&M	+ 62.8	- 302.6	- 142.8
Total Capital	+ 149.7	+ 201.4	+ 316.2
Total 20 Year Cost	+ 212.5	- 101.2	+ 173.4

TABLE 6
DELTA COST - IUS WITH FUELL CELLS
SOLID WASTE OPERATION 24 HOUR/DAY, 6 DAYS/WEEK

	Incineration	URDC	Barber-Colman
Capital ($1,000's)			
Solid Waste	+ 86.8	+ 132.2	+ 212.8
Electrical Power (Fuel Cell)	- 24.1	+ 1.4	- 4.3
Absorption Chillers	+ 12.8	+ .1	+ 5.5
Compression Chillers	- 11.5	- .1	- 5.0
Total Capital	+ 64.0	+ 133.6	+ 209.0
Annual O&M ($)			
Solid Waste	+11,506	+ 4,000	+ 5,865
Electrical Power (Fuel Cell)	0	0	0
Operating Crew	+29,010	+29,010	+29,010
Subtotal O&M	+40,516	+33,010	+34,875
Fuel	- 6,765	-27,339	-16,762
Total O&M	+33,751	+ 5,671	+18,113
20 Year Costs ($1,000's)			
20 Year Fuel	- 87.6	- 354.0	- 217.1
20 Year Other O&M	+ 356.5	+ 290.5	+ 306.9
Total 20 Year O&M	+ 268.9	- 63.5	+ 89.8
Total Capital	+ 64.0	+ 133.6	+ 209.0
Total 20 Year Cost	+ 332.9	+ 70.0	+ 298.8

capital costs for the 100 apartment unit systems operating at 8 hours/day, 7 days/week were taken from the 24 hour/day curves, but at a capacity of 15.4 TPD of refuse and 10.3 TPD sludge determined as follows:

$$\frac{6 \text{ TPD (Refuse)} + 4 \text{ TPD (Sludge)} \quad x\ 7 \text{ days}}{24 \text{ hours/day } x\ 6 \text{ days}} = 972 \ \frac{\text{lb}}{\text{hr}}$$

$$\frac{6 \text{ TPD (Refuse)} + 4 \text{ TPD (Sludge)} \quad x\ 7 \text{ days}}{8 \text{ hours/day } x\ 7 \text{ days}} = 2500 \ \frac{\text{lb}}{\text{hr}}$$

$$\frac{2500}{972} \quad x\ 6 \text{ TPD} = 15.4 \text{ TPD}$$

For the Barber-Colman system, it was assumed that the heat recovery from the 1400°F burner exhaust gases could be accomplished by ducting them into the electrical generation heat recovery unit. It was assumed that this would increase the cost of this heat recovery equipment by about 25 percent over it's baseline cost. This amounts to $5,000 which was included in the pyrolysis system costs for convenience.

Operation and maintenance costs for the pyrolysis systems in an IUS were assumed to be the sum of the component maintenance costs. Labor adjustments for 24 hour operation were considered separately for the IUS. It was assumed that off site disposal

of the pyrolysis residue would be free. In reality, it will probably be a salable item.

INCINERATION COSTS

The incinerator capital costs used for the pyrolysis/IUS integration study are based on the MIUS Design Study Report less the collection carts and a few items which would be required by the IUS with or without a solid waste disposal system. The incinerator system costs for the 500 and 1000 unit systems in the MIUS Design Study Report were adjusted on a linear basis from the 833 lb/hr capacity of the baseline incinerator system in the report to 972 lb/hr and 2,500 lb/hr capacities to match the duty cycle requirements of this study.

Table 7 shows the values used in the MIUS Design Study with the adjusted costs for burn rate capacity and the deleted carts, etc. in the Washington, D. C. area. Table 8 shows the component cost for the 833 lb/hr incinerator system in Chicago without carts. The adjustment to Washington, D. C. area was made by applying a 92.8 percent factor, and the adjustment for deletion of the carts and other components was made by applying a 78.2 percent factor.

The annual maintenance costs were adjusted by the same factors as the basic system costs following the same procedure uses in going from a 500 to 1000 unit complex in the MIUS Design Study Report. Off site disposal of the residue was charged at $7,280

TABLE 7
INCINERATOR SYSTEMS COSTS

Burn Rate R	Duty Cycle Basis	Cost W/O Collection Carts, Etc.	Cost W/Carts, Etc.*
833*	500 Unit IUS 12 Hr/Day, 7 Days/Wk	79,000	101,000
972	1000 Unit IUS 24 Hr/Day, 6 Days/Wk	86,800	N/A
1,667*	1000 Unit IUS 12 Hr/Day, 7 Days/Wk	160,700	161,000
2,500	1000 Unit IUS 8 Hr/Day, 7 Days/Wk	172,500	N/A

*Values from the MIUS Design Study Report

TABLE 8
INCINERATOR SYSTEM COSTS
833 LB/HR CAPACITY, CHICAGO, WITHOUT COLLECTION CARTS
REFERENCE MIUS DESIGN STUDY REPORT

	Capacity	Maintenance
Loader	$10,300	$ 310
Incinerator	21,000	630
Auto Ash Removal	5,300	160
Heat Recovery Boiler	40,000	2,000
Controls	700	10
Oil Burners	500	100
Flame Sensor	500	100
Ash Storage Container	1,200	10
Auger	1,200	35
Installation Hardware	4,400	200
Maintenance Hardware	--	1,060
	$85,100	$4,615

per year based on the total refuse processed.

ELECTRICAL POWER AND HVAC SUBSYSTEMS

The variations of installed capacities of electrical generators is shown in Tables 9 and 10 with the associated cost impacts. Tables 11 and 12 show the installed capacities of HVAC equipment and associated cost impacts. The equipment sizing was based on the peak loads at 4:00 p.m. and 8:00 p.m. on a design summer day. These loads are shown in Table 13. The cost deltas were based on the economic groundrules presented in Appendix E3.

IUS FUEL COSTS

The IUS fuel consumption and cost delta results are summarized in Tables 14 and 15. The primary fuel requirements for the IUS are taken from the energy balance flow charts (Appendices D3 and #2) for the IUS.

TABLE 9
ELECTRICAL POWER SUBSYSTEM
COST DELTA DIESEL GENERATORS

	No Waste Disposal	Incineration	URDC	Barber-Colman
Peak Load (KW)	2,522	2,427	2,528	2,507
Installed Capacity (KW) (Pk Ld x 4/3)	3,362	3,236	3,370	3,343
Delta Installed Capacity (KW)		- 126	+ 8	- 19
Delta Cost ($195/KW)		-24,570	+ 1,560	- 3,705
Quant of Dual Fuel Engines Required (Pyrolysis Gas Utilization)	0	0	2	2
Delta Cost for Dual Fuel ($15,000 Ea)		0	+30,000	+30,000
Delta Capital Cost		-24,570	+31,560	+26,295
Delta Annual Maintenance (5.8% of Dual Fuel)		0	$ 1,740	$ 1,740

TABLE 10

IUS ELECTRICAL POWER SUBSYSTEM COST DELTA, FUEL CELLS

	W/O Disposal	Incineration	URDC	B. C.
Peak Load (KW)	2,591	2,498	2,597	2,575
Installed Cap. (KW)	3,455	3,331	3,462	3,433
Delta KW	--	- 124	+ 7	- 22
Delta Cost $ (@ $195/KW)	--	-24,180	+1,365	-4,290

No Delta O&M considered for fuel cells.

TABLE 11
IUS HVAC SUBSYSTEM COST DELTA DIESEL GENERATORS

	W/O Disposal	Incineration	URDC	B. C.
Installed Absorption Chillers (Tons)	364	475	365	413
Delta Capacity (Tons)	--	+ 111	+ 1	+ 49
Delta Cost @ $115/Ton	--	+$12,765	+$115	+$5,635
Installed Compression Chillers (Tons)	838	727	839	791
Delta Capacity (Tons)	--	- 111	- 1	- 47
Delta Cost @ $104/Ton	--	-$11,544	-$104	-$4,888

TABLE 12

IUS HVAC SUBSYSTEM COST DELTA FUEL CELLS

	W/O Disposal	Incineration	URDC	B. C.
Installed Absorption Chillers (Tons)	287	398	288	335
Delta Capacity (Tons)	--	+ 111	+ 1	+ 48
Delta Cost @ $115/Ton	--	+$12,765	+$115	+$5,520
Installed Compression Chillers (Tons)	917	806	916	869
Delta Capacity (Tons)	--	- 111	- 1	- 48
Delta Cost @ $104/Ton	--	-$11,544	-$104	-$4,992

HVAC O&M cost delta is negligible.

TABLE 13
DESIGN SUMMER DAY LOADS
USED FOR SIZING ELECT GENERATORS AND CHILLERS

	4:00 P.M.	8:00 P.M.
Domestic Elec Demand KW (Does not include comp. chillers or solid waste)	1,600	2,000
A/C Load Tons	1,173	960

TABLE 14

ANNUAL IUS FUEL COST DELTA DIESEL GENERATORS

		W/O Disposal	Incinerator	URDC	B. C.
24 Hour/Day, 6 Day/Week					
Primary Fuel	(10^6 Btu)	107,076	108,671	92,255	101,342
Start Up Fuel	(10^6 Btu)	0	30	182	87
Total Fuel	(10^6 Btu)	107,076	108,701	92,437	101,429
Delta Fuel	(10^6 Btu)	0	+ 1,625	-14,639	- 5,647
Delta Cost	($)	0	+ 3,006	-27,082	-10,447
8 Hour/Day, 7 Day/Week					
Primary Fuel	(10^6 Btu)	107,076	108,671	92,255	101,342
Idling Fuel	(10^6 Btu)	0	548	408	146
Total Fuel	(10^6 Btu)	107,076	109,219	92,663	101,488
Delta Fuel	(10^6 Btu)	0	2,143	-14,413	- 5,588
Delta Cost	($)	0	+ 3,964	-26,664	-10,338

TABLE 15
ANNUAL IUS FUEL COST DELTA FUEL CELLS

	W/O Disposal	Incinerator	URDC	B. C.
24 Hour/Day				
Primary Fuel (10^6 Btu)	95,374	91,687	80,414	86,226
Start Up Fuel		30	182	87
Total Fuel	95,374	91,717	80,596	86,313
Delta Fuel		-3,657	-14,778	- 9,061
Delta Cost		-6,765	-27,339	-16,762
8 Hour/Day				
Primary Fuel (10^6 Btu)	95,374	91,687	80,414	86,226
Idle Fuel (10^6 Btu)		548	408	146
Total Fuel	95,374	92,235	80,822	86,372
Delta Fuel		-3,139	-14,552	- 9,002
Delta Cost		-5,807	-26,921	-16,654

The start up fuel for the incinerator was ratioed from the MIUS Design Study Report baseline requirement in the same manner as the incinerator system. The start up and idle fuel requirements used for the pyrolysis systems and the incinerator idle are shown in Table 16. Fifty-two start ups per year were assumed for the 24 hour/day operation, and 16 hour/day idle for 365 days per year were assumed for the 8 hour/day operation.

	Incinerator	URDC	B. C.
Fuel/Start Up (10^6 Btu)	.583	3.5	1.7
Fuel for Idle (Btu/Hr)	93,800	70,000	25,000

TABLE 16
FUEL START UP AND IDLE REQUIREMENTS

LABOR COST DELTA

The labor cost delta is taken directly from the Economic Ground Rules Appendix E-3. A total of $29,010/year is assessed for third shift coverage, 6 day/week, for the solid waste system operating 24 hours/day. No cost delta is assessed to 8 hour/day operation of the solid waste subsystem since it is operated by IUS personnel available by two shifts per day.

APPENDIX F1

PYROLYSIS FUEL GAS UTILIZATION

F1

PYROLYSIS FUEL GAS UTILIZATION

Introduction

There are many aspects to the utilization of the fuel gases that could be produced from a waste pyrolysis system. The major relevant ones are discussed in the following sections. However, all discussions are based on the premise that pyrolysis (Barber-Colman or URDC) fuel gas is not directly suitable for pipeline or synthetic natural gas (SNG). That is, even the medium Btu pyrolysis gases would require considerable added processing before they would be suitable for pipeline applications. Methanation would be required, and this is a costly step in dollars as well as in energy. Furthermore, it is not a well developed process, and the major development efforts are directed towards the very large SNG facilities which would be orders of magnitude larger than a waste processing plant. In addition to increasing the fuel gas heating value to the thousand Btu per cubic foot HHV level, the process also would have to stabilize the composition to a relatively high degree.

As a result of these considerations, it was felt that the complexity, cost, energy loss and added technical risk involved in upgrading any pyrolysis gas to SNG would be excessive.

A further assumption is that it is assumed that the gas will not be distributed for residential uses such as stoves, driers,

individual water heaters, etc. This type of distribution is quite feasible although it would require a higher level of compositional stability than the large scale uses discussed. The major problems would be the high CO content of any of the pyrolysis gases and the need to make custom modifications to a relatively large number of low cost appliances. The modifications would be necessary for any pyrolysis gas since standard residential appliances are available only for natural or liquified petroleum (LP) gas.

Fuel Gas Classes

It is useful to place fuel gases in very rough categories in order that the pyrolysis gases can be compared to each other and to other more common fuel gases. A useful division is the following:

- Highly Dilute, Energy Mainly in H_2, CO
- Moderately Dilute, Energy Mainly in H_2, CO
- Slightly Dilute, Energy Mainly in H_2, CO
- Slightly Dilute, Energy in H_2, CO, Hydrocarbons
- Natural Gas
- LP Gas

The major entry in the first category is blast furnace gas with a higher heating value (HHV) of typically 92 Btu/ft^3. The second category includes the assortment of gases made from coal or residual oil by some form of partial oxidation by air such as

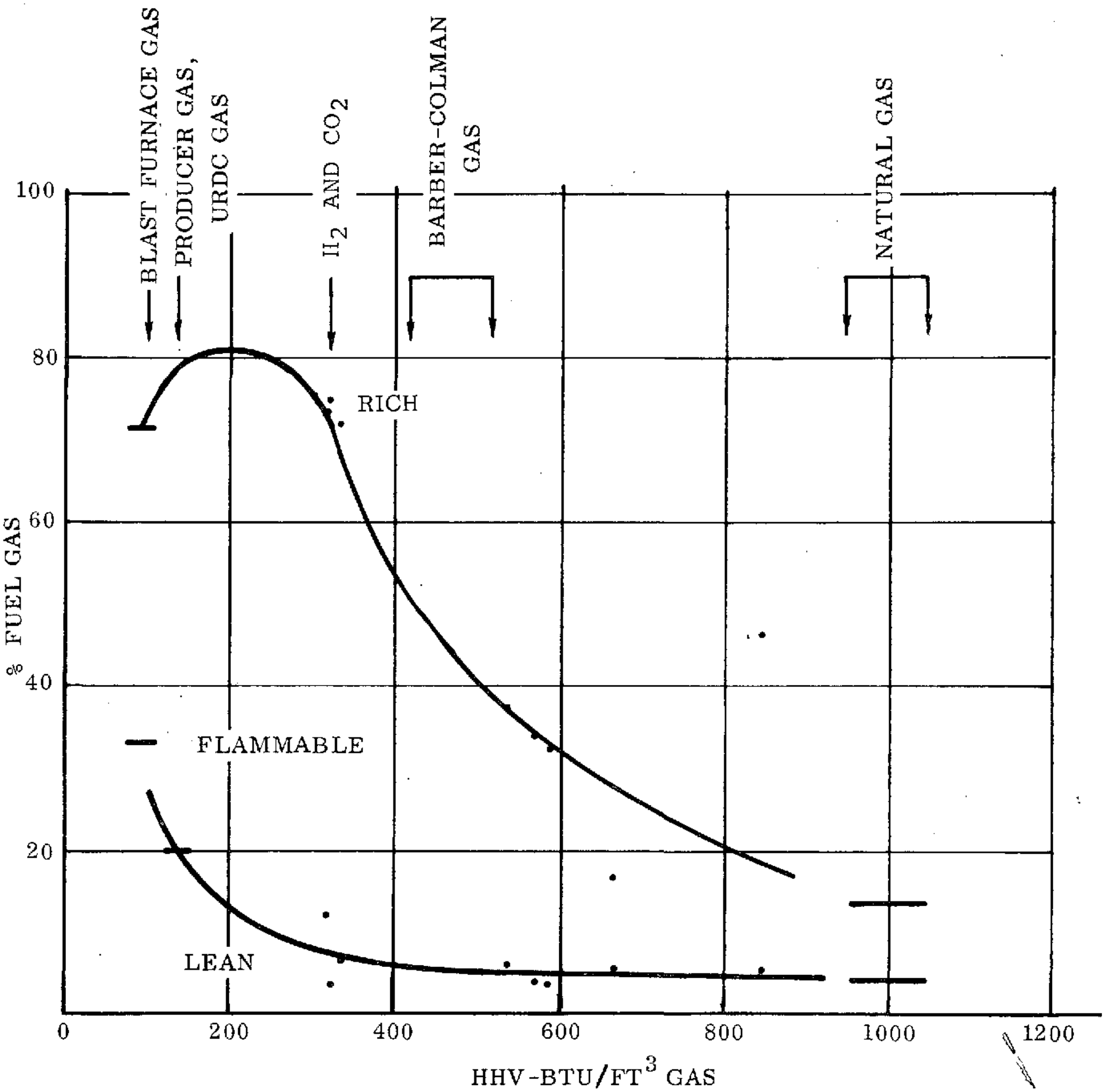
the traditional producer gas. It also includes the gas that is produced by the URDC system. The next two categories include a host of manufactured and by-product gases. The major differences between them are in the heating value split between H_2 and CO versus hydrocarbons and in how high the hydrocarbons are. The Barber-Colman product gas is in this category. The next category is natural gas which is mainly CH_4 and typically has an HHV of about 1,000 Btu/ft^3. Finally, we come to the LP gases, basically propane and butane which can be liquified by pressure alone. In practice, they are always stored as liquids. They have HHV's of 2,300 and 3,000 + Btu/ft^3 respectively.

It is very important to note that the usual categorization of fuel gases by their higher heating value per unit volume of fuel can be highly misleading. In terms of basic thermodynamic combustion performance (e.g., flame temperature, energy density of products, etc.), the slightly dilute fuel gases, natural gas, LP gas, and the conventional liquid hydrocarbon fuels all have essentially similar performance. Both CO and hydrogen (HHV's of 321 and 325/Btu^3) have higher flame temperatures than the conventional fuels so that the slightly dilute gases, which have most of their energy in H_2 and CO but have some dilution of CO_2 and/or N_2, still have very good combustion performance - which, in fact, can slightly exceed that of natural gas.

The producer category gases are dilute enough so that their thermodynamic/combustion performance is lowered only slightly below that of the conventional fuels. Flammability limits are still quite wide, and flame stability is not a problem. In the highly dilute category typified by blast furnace gas, the dilution is large enough so that flame stabilization may become difficult under some circumstances. Energy utilization efficiency also becomes noticeable poorer for blast furnace gas because of the relatively low energy density levels.

The general combustion stability characteristics of the various gases is illustrated by the flammability limit data given in Figure 1. Much of the differences can be explained by the amounts of H_2 and CH_4 in the gas. Hydrogen burns very smoothly and stably over wide combustion limits; CH_4 is the most chemically stable of the hydrocarbons and, therefore, has relatively narrow combustion stability limits. Thus, the producer gases, such as the URDC system product, still have quite wide combustion stability limits even though they are somewhat dilute. The Barber-Colman product also contain significant quantities of H_2 and has rather wide limits. However, it would appear that its rich limit might vary by quite a bit within its range of expected composition variation.

One fuel gas of some interest that does not fall in any of the above categories - even though its HHV does - is raw digester



FLAMMABILITY LIMITS OF VARIOUS FUEL GASES

FIGURE 1

gas. That is, the unscrubbed gas produced from the anaerobic digestion of sewage sludge or other organic wastes. Typically, this gas is on the order of 50% CH_4 and 50% CO_2. Unless the CO_2 is scrubbed out, this is a diluted gas with thermodynamic/combustion performance somewhat above producer gas but below all of the other medium Btu gases even though its HHV falls into the upper medium Btu category.

Some of the fuel gases (e.g., producer gas) are often used in the raw gas form as well as in the form of a scrubbed, ambient temperature gas. The raw gas usually contains condensable hydrocarbons (tars and oils) and sometimes a significant quantity of inorganic particulate matter. The sensible heat can be significant as in the case of conventional coal gas producers which may operate with raw gas temperatures of well over 1,000°F.

Historic Aspects

The state of the technology of utilization of particular gases, as well as the range of off-the-shelf equipment available for utilizing the gas, is a strong function of historic and economic aspects that are not directly related to the technical difficulties involved.

Coal in general, and coal derived producer gas in particular, once were very important industrial fuels. For example, Trinks(1) states that "Until about 1920, raw producer gas was

the standard gaseous fuel for large furnaces in the United States. Clean, cold, producer gas was also used wherever improved control of the fuel was indicated." However, that era ended with the advent of cheap natural gas. The pipeline came, coal prices rose, and labor costs involved in processing coal in any coal derived gas facility rose sharply. Natural gas was priced on the basis of production costs - which are very low - and, in practice, the supply was treated as essentially infinite. Natural gas took over, not so much because it was better, but simply because it was cheaper. Certainly for the operator of any type of manufactured gas facility, natural gas was much easier to deal with since his function was reduced from production (starting with a dirty raw material - coal) to simply distribution.

As a result of these factors, gas fuel usage has been restricted to natural or LP gas for most applications, along with some in plant by-product gas utilization (e.g., blast furnace gas, coke oven gas) usually in relatively large installations. Thus, most present day gas burning equipment is designed for use with natural or LP gas simply because that is the only kind of gas in general use.

In the last year, our society as a whole has reached an increased awareness of the limitations on energy availability. As a result, there is much more interest in using all forms of energy

and using them efficiently. For example, there has been renewed interest in the old gas producer[2]. Thus, the energy technology picture can be expected to change greatly, but this change will take a great deal of time.

A basic requirement for pyrolysis gas production systems is that they must be designed so that the use of the pyrolysis gas will not jeopardize the main system operation. For scrubbed gas systems, this is a function of the scrubber and not the pyrolysis process itself. Since the basic scrubber requirements are the same for the Barber-Colman and URDC systems, there is no basis for differentiating between them on this regard. For raw gas burning, systems have to be carefully designed to insure that any deposition problems would not impair the function of the main fuel system.

Baseline IUS Prime Mover Pyrolysis Gas Integration

The principle prime movers being considered in the Pyrolysis Study are diesel engine generator sets and fuel cell power generation. The sections below deal with the utilization of pyrolysis gas in these power generating approaches. A later section will deal with other potential uses of pyrolysis gas in alternate prime movers and in burner applications.

Diesel Engines - Internal combustion engines come in many variations and can operate on many fuels. The most common gas engine:

are designed to run on natural gas because this is the most available fuel. However, gas engines have been run on many fuels including blast furnace gas, which is a significantly lower grade of fuel than producer gas (1,3,4). The efficiency of a low compression gas engine is usually poorer than an oil diesel, especially at part load.

Dual fuel engines which can fire gas or oil in combination usually are designed for natural gas, and relatively few manufacturers have had experience with other fuel gases.

A variation on the dual engine is "fumigation" of oil diesels[5]. This is simply the introduction of some fraction of the fuel energy input, usually 20% or less, into the air inlet as a vapor. This is related to a family of other charge preconditioning processes that have been developed or are under development for the purpose of improving engine performance[6].

In these experiments, increased performance could be obtained by preconditioning. The objective is to decrease knock by decreasing the ignition delay in the cylinder and obtain more complete combustion. The methods used were by injecting directly into the cylinder or carbureting into the air stream or manifold (fumigating) a small amount of fuel (either diesel oil or more volatile fuels) such that it initiates combustion when the primary fuel injection begins rather than after the normal delay.

The result is lower specific fuel consumption and smoother operation (less knock and wall scrubbing) which will result in reduced maintenance costs. Small increase in engine efficiency (energy out divided by total energy in, including both main fuel and fumigation fuel) have been obtained in some cases. However, efficiency gains or losses tend to be quite small so that the assumption of constant efficiency with or without fumigation is a reasonable one.

The fumigation approach is also the simplest from a hardware standpoint. The basic requirement is that the fuel gas be introduced into the air inlet with sufficient distance for complete mixing with the air before manifolding to the cylinders. Engine costs for a fumigated engine would be very little more than the cost for a basic oil diesel. The major potential drawback to fumigation is the possible loss of the fuel gas into the exhaust stream. For example, most diesels have considerable valve overlap to assist in scavenging the burned charge. If the scavenging air also contains fuel gas, as it would in fumigation, some fuel gas will be lost. In an IUS application, this fuel carried through by scavenging would burn in the exhaust, and the energy would be recovered as higher grade heat.

Dual fuel engines avoid fuel gas loss by valving the fuel gas into the air manifold with appropriate valve timing. However, dual fuel engines are designed to allow the gas to carry most of

the load and not just a small fraction as in fumigation and the IUS application. Although some dual fuel engines are designed to utilize all of a fluctuating gas output with engine power output controlled by varying the oil fuel, this is not the usual mode of operation. Most dual fuel engines are designed to use either the gas or the oil with no modulation of relative proportions. On gas operation, the oil is used basically only to provide ignition and, therefore, supplies only a small proportion of the total energy.

Therefore, the best choice of system for an IUS with diesel prime movers appears to be to fire the gas in the main IUS engines by either fumigation or some variation on the dual fuel engine. Fumigation is the best choice, provided that scavenging would not cause excessive gas loss or excessive unburned hydrocarbon emissions. If these are a problem, a dual fuel type of inlet valve configuration (but with no throttling of the air) would be indicated. Since the standard dual fuel engine valves and manifolds would be designed to allow the engine to run essentially full load on gas, while the IUS application would be limited to perhaps 20% of the load on gas, available gas flow area should not be a problem even with the low Btu air gasifier product.

Efficiency - The exact trade off between main fuel consumption and fuel gas consumption would depend on factors such as the engine configuration, load, load split between gas and main

fuel, main fuel composition and fuel gas composition. However, in the range of load splits that might be anticipated in an IUS application, the first order factors should predominate. These would indicate that one Btu LHV of any fuel in the cylinder would be equivalent.

These first order effects can be outlined as follows: for a given load (less than full load) and engine, a given amount of energy (LHV) must be introduced to the cylinder. Therefore, the LHV per ft^3 <u>mixture</u> in the cylinders is a constant no matter what the fuel. For the low Btu fuel, the dilution of the mixture LHV is accomplished partly by air and partly by the N_2 contained in the gas. For a medium Btu fuel, the diluent is simply air. From a first order thermodynamic standpoint, the difference between air and N_2 as diluents is negligible.

The only differences between fuel gases then would be as stoichiometric or full load conditions were approached. The low Btu gas, because of its nitrogen dilution, will leave somewhat less oxygen at a given load than will the Barber-Colman gas. This does not affect efficiency for a given load and engine, but only maximum output for a given engine. The engine generator for an IUS would on the average run at about 75% base load rating, and this situation would, for all practical purposes, never be seen.

The magnitude of this effect can be estimated from the LHV per ft^3 of a stoichiometric. This is 70, 86 and 87 Btu/ft^3 for the

air gasifier product, the Barber-Colman product, and natural gas respectively. The equivalent LHV for stoichiometric No. 2 oil is 97.2 Btu/ft^3. A reasonable assumption is that oil combustion requires 25% excess air (a typical minimum for diesel engines) while gas combustion can be at stoichiometric. Furthermore, a base loaded engine is limited to less than its maximum output capacity to insure adequate life and, therefore, does not even approach its maximum output unless it is run at overload conditions. Then, if we assume the maximum engine output is 110% of the full load rating on oil or natural gas, and the load is carried 20% by pyrolysis gas/80% by fuel oil, we get the following results:

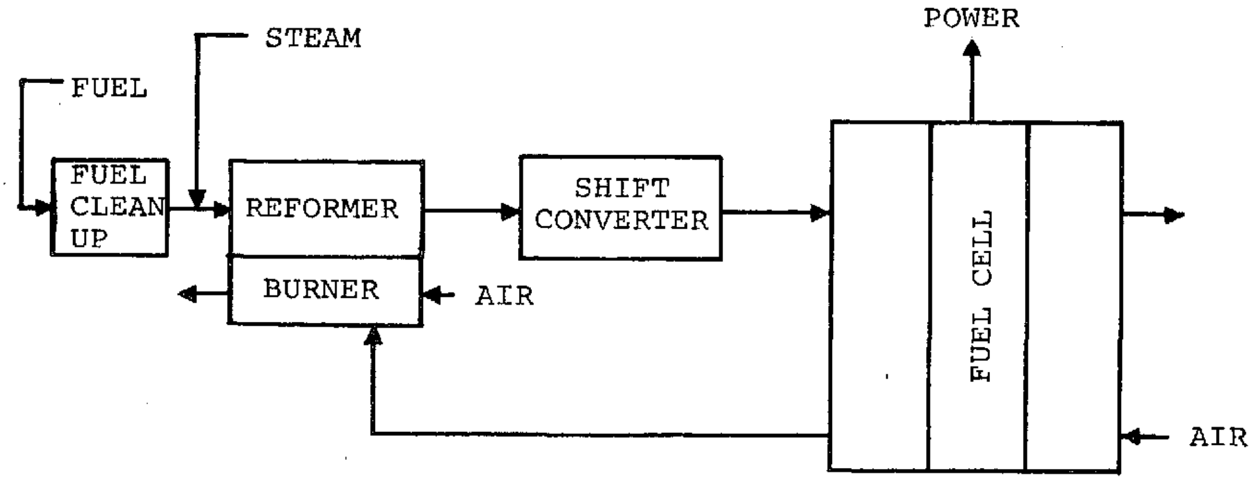
	Max, Input Or Output	(Max, Output) / (Max, Output) Natural Gas)	Max Output % Of Full Load
Air Gasifier Product	76 Btu/Ft^3	96%	105%
Barber-Colman Product	79 Btu/Ft^3	100%	110%
Natural Gas	79 Btu/Ft^3	100%	110%

As can be seen, the maximum output limit when mixed firing with a low Btu gas is quite small and in all probability negligible. Furthermore, the need to oversize the prime mover to allow for this affect can be avoided by flaring fuel gas for the rare conditions when the IUS engine must operate at near maximum or overload conditions.

Fuel Cell Systems - Fuel cells such as the Pratt & Whitney Aircraft FCG-1[7] are basically hydrogen consumers (i.e., the fuel cell electrochemically reacts H_2 and O_2 to produce electric power). Therefore, conventional fuels must first be converted to a high hydrogen content stream. This is usually done by steam reforming which catalytically converts a hydrocarbon plus water to a mixture consisting mostly of H_2, H_2O, CO and CO_2. This is followed by shift conversion to eliminate CO in favor of hydrogen. Since reforming is a rather strongly heat absorbing reaction, fuel not consumed by the fuel cell is burned to provide the required process heat.

The detailed evaluation of the performance of a fuel gas plus oil fuel powered fuel cell systems requires the optimization of the internal energy balances in the reformer/fuel cell system. This analysis was beyond the scope of the Pyrolysis Study, and approximations were made by Hamilton Standard as a result of discussion with Pratt & Whitney Aircraft.

Basic System - The major components of a fuel cell system for power generation are shown schematically below. The various heat recovery and heat rejection systems are not shown.



For a first generation system, the fuel would have to be something like natural gas or a clean liquid hydrocarbon such as naphtha. The fuel used for performance projections was taken to be C_xH_{2x} which is representative of a clean liquid hydrocarbon. Natural gas is also a likely fuel for an IUS application. However, for the purposes of performance projection, there is no fundamental difference between the fuels.

Both reforming and shift conversion are catalytic processes and are susceptible to poisons, particularly sulfurs, chlorides and olefinic hydrocarbons. The sulfur and chloride requirements are very tight so that a second stage of pyrolysis gas scrubbing would be required. This would probably use activated carbon or possibly ZnO. The main potential for poisoning by olefins is

ethylene. However, at the load split between pyrolysis gas and primary fuel, the ethylene would be within acceptable limits (1%) for both pyrolysis gases.

The reforming process is carried out at 1,400°F to 1,600°F and is endothermic. Thus, considerable heat is required. The reaction can be represented as follows:

$$1/X\ C_xH_{2x} + 2.75\ H_2O \rightarrow y\ CO + (1-y)\ CO_2 + (3-y)\ H_2 + (.75+y)\ H_2O$$

In order to increase the hydrogen production, CO can be converted to CO_2 via the water gas shift reaction, provided that temperatures are lowered to the point where the equilibrium is favorable (i.e., 500 - 600°F). This reaction is:

$$CO + H_2O \longrightarrow CO_2 + H_2$$

The high hydrogen concentration gas is fed to the fuel cell which normally consumes over 75% of the hydrogen. The remaining H_2 goes back to the reformer to supply the heat required by the reformer.

URDC Gas - The air gasifier product would contain approximately 80% of its energy in hydrogen after shift conversion. Therefore, there would be no point in reforming it in an IUS application and it would be introduced between reformer and shift converter. The fuel cell system would be base loaded on the pyrolysis gas, and the main fuel would be throttled to control

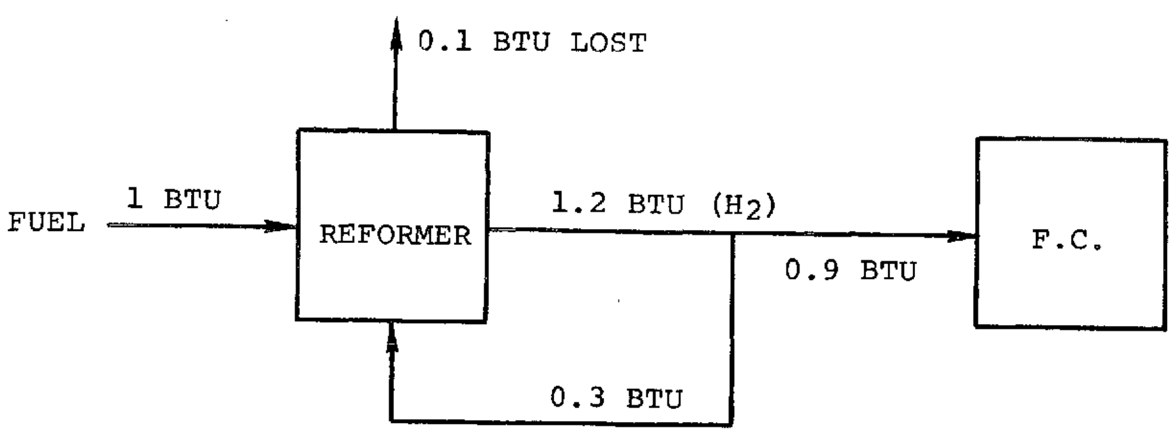
output - quite analogous to the diesel system. The pyrolysis gas would be introduced along with sufficient steam for shift conversion. A separate steam control would be required from the main fuel steam control.

The gas stream going to the reformer would be diluted somewhat by the nitrogen from the pyrolysis gas. However, fuel cell performance is limited on the air side rather than on the hydrogen side. Hydrogen utilization is set by the energy required to reform, and the utilization can be significantly increased before a noticeable reduction in performance is obtained. Since roughly 16% of the energy comes from the pyrolysis gas, which is about 50% nitrogen, typical dilution levels are in the order of 10% or less which should have a negligible effect.

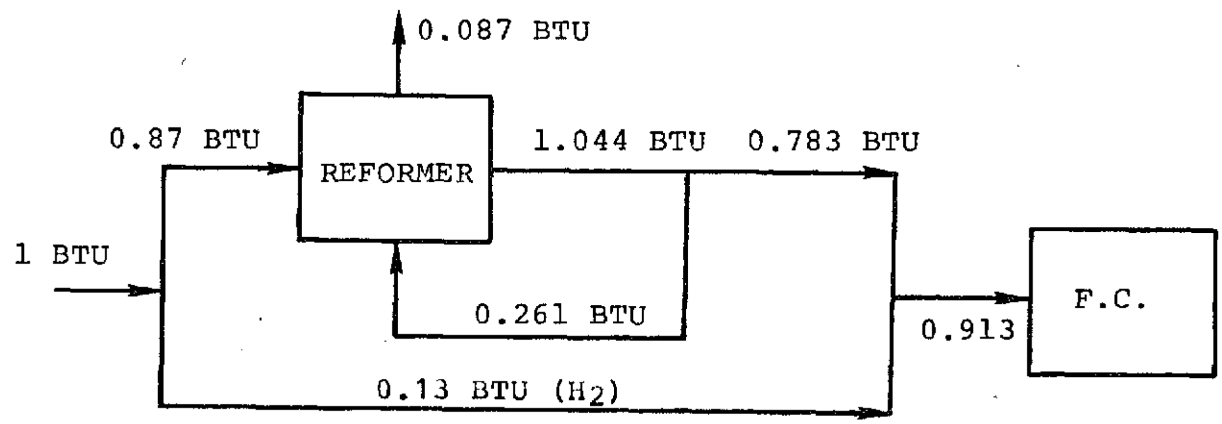
<u>Barber-Colman Gas</u> - This gas contains less than 30% of its energy in hydrogen after shift conversion. Therefore, it would be introduced into the reformer along with the primary fuel. If the primary fuel were a liquid hydrocarbon, then the two fuel streams would be introduced separately with separate steam supplies. The pyrolysis gas also would have separate pretreatment (e.g., activated charcoal). If the primary fuel were natural gas, the two fuels probably could be mixed at the system inlet. The same pretreatment would then be used for both. The steam controls still would have to sense the two fuel flows separately since each would have different water requirements.

Performance/Power - Both pyrolysis gases should give a small gain in system electric generation efficiency. This is because both already contain hydrogen, thereby, reducing the energy loss associated with reforming. However, since the Barber-Colman gas has a much lower fraction of its energy in hydrogen, the gain associated with it is much smaller.

The magnitude of the efficiency improvement can be estimated as follows: Normally, the fuel cell would use about 75% of the hydrogen delivered to it and return the remaining 25% to supply the reformer heat needs. However, all of this 25% is not lost since reforming produces approximately 20% more energy chemical in hydrogen than there is chemical energy in the original fuel. Thus, a system with full reforming of the fuel can be represented as follows:



The air gasifier product supplies about 16% of the total energy and has about 79% of its energy in hydrogen. Thus, 13% of the total fuel does not have to be reformed and the combined system performance becomes:

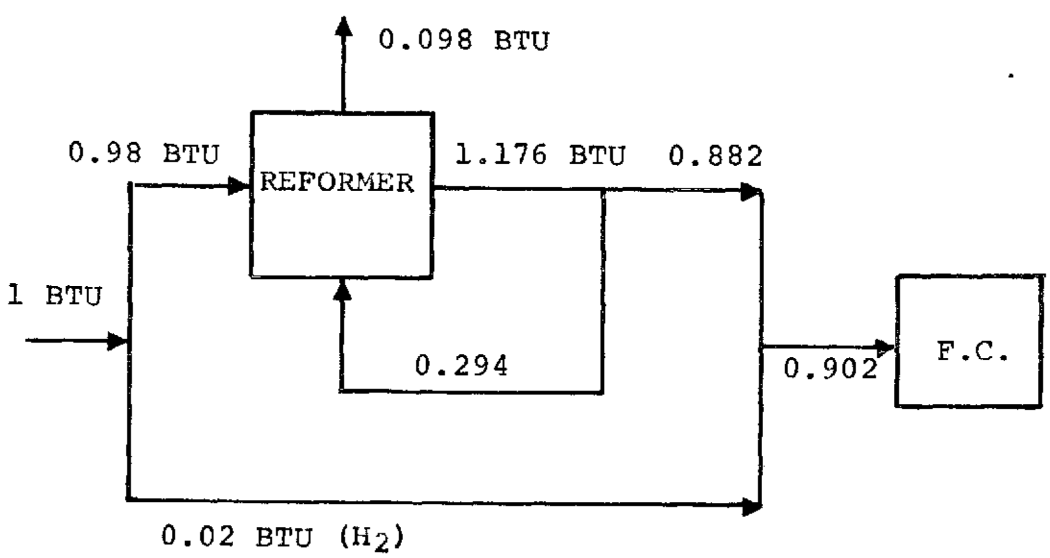


The total system efficiency improvement, thus, is 1.4% (0.913/ 0.9 = 1.014). An alternative way of representing the improvement is to consider that a hydrogen fuel is worth 11% more than a fuel that has to be reformed (1/0.9 = 1.11). The air gasifier product contains 79% hydrogen. Thus, the efficiency gain is 9% (79% of 11%), and 1 Btu air gasifier product is worth 1.09 Btu's of primary fuel. The overall gain again is 1.4% (16% of 9%).

A potential problem area is excessive dilution of the fuel gas supplied to the fuel cell. The critical point is the hydrogen concentration in the gas leaving the fuel cell. Two effects combine to lower fuel cell exit hydrogen partial pressure: lowered reformer hydrogen requirements and nitrogen dilution.

Normal hydrogen utilization is 75%, and the limited available evidence would indicate that this could be increased to over 85% without noticeable performance deterioration. The equivalent effect of the two factors discussed would be considerably less than an 85% hydrogen utilization. Therefore, no fuel cell performance deterioration would be expected.

At best, the Barber-Colman gas only would supply an average of 6% of the total load. Roughly 28% of its energy (after shift conversion) would be in hydrogen. Therefore, something less than 2% of the hydrogen would come directly from the pyrolysis gas. The energy balance becomes:



The improvement in overall system efficiency, thus, is approximately 0.2% (0.902/0.9 = 1.002). Comparing the Barber-Colman gas to the primary fuel, one Btu of Barber-Colman product is worth approximately 1.03 Btu's of primary fuel for a 3% gain (28% of 11%). On a total system basis, the gain is again 0.2% (6% of 3%).

Performance/High Grade Heat - A reduction in fuel input for a given power output means that there also will be a reduction in heat rejection. Fuel cell systems, and particularly the reformer which is where most of the internal heat requirements are, are rather thoroughly optimized for maximum heat recovery. As a result, a great deal of waste heat is rejected at temperatures too low for further utilization in an IUS.

As a rough approximation, most of the heat rejected from the reformer side is unrecoverable, while most of the high grade heat (i.e., 250^{o}F or better) comes from the fuel cell itself. As a result, the reduction in reforming requirements associated with the pyrolysis gases should not change the high grade heat rejection but instead come at the expense of low grade heat.

There is one area where there actually might be an increase in the amount of high grade heat even though the total heat rejection is down. That is, the stoichiometric water requirement for reforming is two mols H_2O per mol C. The stoichiometric requirement for shifting CO to CO_2 is only 1 mol H_2O per mol C. Thus,

the stoichiometric steam requirement is reduced from 2 mols H_2O per mol of total C in the fuel to 2 mols H_2O per mol of C for that part of the pyrolysis gas that has to be reformed, plus 1 mol H_2O per mol CO for CO that must be shifted. This reduction in internal steam consumption means that high grade energy will be available to supply steam requirements external to the fuel cell system. Furthermore, it also results in a second level of reduction in the quantity of low grade heat rejection. This can be a significant advantage since the rejection of low grade waste heat to ambient tends to be expensive from a hardware standpoint (as for example in air cooled condensers).

Alternate Applications - The other areas of interest, though not for an IUS, are applications where the pyrolysis gas might supply all or nearly all of the fuel input to a fuel cell system. The major points that should be considered include:

1. As the amount of reforming necessary is reduced, there is less need for heat within the fuel cell system. Therefore, very high hydrogen utilizations are required unless there is a use for heat in the gasification process.
2. If any reforming or shift conversion is required, the olefin content of the pyrolysis gas may become excessive.

As a result of these considerations, we could draw the following conclusions with respect to the Barber-Colman product:

1. Reforming would still be required because of the relatively low fraction of energy in hydrogen.
2. The high olefin content of the Barber-Colman gas (measured values given in the Barber-Colman proposal range from 4.0 to 7.7% ethylene) may exceed the allowable limits for the reforming catalyst.

The following conclusions could be drawn for the air gasifier product:

1. Reforming probably still would be required. Since the reformer is heat transfer limited, reformer design should become significantly easier and losses lower.
2. The olefin content should be within acceptable limits although there might be operating conditions under which the ethylene content would be marginal.
3. Fuel cell exhaust could be burned to supply heat for the small amount of reforming still required as well as for preheating the gasification air. The total heat requirement probably would be significantly lower than the normal reforming load.
4. The high dilution in the fuel cell exit might result in flame temperatures too low for a conventional burner. Catalytic burners, as developed for fume incineration applications, probably would be adequate.

5. The combination of dilution and lower than normal needs for fuel cell exhaust hydrogen would require higher than normal effective hydrogen utilization rates.

In summary, it would appear that the Barber-Colman gas could be used only if ethylene is within acceptable limits. If ethylene is within acceptable limits, then this gas should give a small amount better performance than natural gas. The air gasifier product definitely could be used for this application, but its performance cannot be estimated without doing considerable analysis (which would have to be done in terms of a specific application). It is quite possible that the performance might exceed the performance of natural gas, but this would require considerable integration of gasifier, reformer, and fuel cell system. The system certainly would have to be somewhat different, both in types of components and in the details of similar components, as compared to a natural gas fueled system.

OTHER POTENTIAL IUS APPLICATIONS

In order to obtain high energy utilization efficiencies in the baseline IUS system, the pyrolysis gas must be usable in the prime mover. However, it is conceivable that other uses for the fuel gas might be found in different IUS situations. In general, the fuel gas applications of most interest would tend to be the large scale residential/commercial ones. However, in some cases an industrial/commercial/residential complex would be possible and in many ways advantageous.

The major commercial/residential use is heat, usually steam or hot water, either for use as direct heat (space heating, hot water) or for cooling (absorption). Industrial applications include the same uses for heat, though often on a larger scale, as well as ovens and furnaces. Industrial use of fuel gases is not limited to their energy value for they also may be used as a process gas. Probably the most common use of this type, outside of the chemical industry, would be for atmosphere and inert gas generation.

Some gas is presently being used to generate on site power either in gas engines, gas turbines, or from steam turbines. In industry, power from steam is usually used just for auxiliaries, air compressors, etc.

Steady Flow Combustion Systems - Burners in one form or another are required in all steady flow combustion applications whether boiler, oven, furnace or whatever. No unusual problems are anticipated with conventional types of burners for clean cold fuel gas utilization in IUS applications whether the gas is a low or medium Btu variety. It is more difficult to utilize a low Btu gas in some high temperature metallurgical or melting furnaces where the furnace temperature approaches the flame temperature of the gas. Many other furnace and oven applications use considerable excess air to limit flame temperature. For these applications, there would be no disadvantage in the use of a low Btu gas.

Boilers use low excess air but do not require high flame temperatures. The major requirement is that the flame characteristics and the boiler internal configuration make a good match.

Internal burner geometry must be tailored to the fuel gas, and this can be expected to cause some problems for a low Btu gas. As the Btu per cubic foot of gas goes down, the burner must handle more fuel and less air (although the change in total quantity handled is about the same). Most burners are designed for natural or LP gas and have appropriate internal geometries. There usually is room to allow geometry modifications well below natural gas levels, but there may not be enough room in some

existing burner hardware to accommodate the changes in fuel/air flow balance required to handle a low Btu gas.

This is by no means a fundamental limitation. Certainly, all evidence indicates that low Btu gas can be burned at combustion efficiencies fully equivalent to natural gas in conventional equipment. Probably the most severe test is the aircraft derivation gas turbine burner which must be designed for minimum volume within a very tight space envelope and still give a high combustion efficiency and a very flat exit temperature profile. Here the evidence is that burners modified to handle the air gas flow balance appropriate to low Btu gas give performance equivalent to those operating on natural gas. Furthermore, in at least one case[8], the low Btu gas had wider stability limits than natural gas (probably due to its high hydogen content).

The use of a raw gas directly from the pyrolysis furnace places additional design limitations on the burner due to the high inlet temperatures and the condensable hydrocarbon content of the gas. Temperature is likely to be a problem for some applications with a raw Barber-Colman gas at 1,000 + degrees F. It should not be a significant problem for the lower temperature product from an air gasifier. Conversely deposit problems would be more serious with the lower temperature gas. According to Union Carbide experience, operation with the fuel gas at saturation

gives few deposit problems because of the non-sticking nature of any condensed hydrocarbons. Commercial fuel additive treatments also have been developed to prevent deposit problems for similar applications such as coke oven gas.

Gas Turbines - IUS studies have favored the diesel or fuel cell over the gas turbine. However, gas turbines would have some significant advantages in those IUS applications which required higher ratios of steam to electrical power, as for example might be found in colder climates. In some cases, gas turbines might be the economic optimum even though their overall energy consumption was slightly higher than the competing diesel system. Although most IUS applications are on the small output end of the gas turbine power spectrum, appropriate engines are available and have been used in relatively small total energy installations.

It would be possible to design a dual fuel gas turbine which could handle a combination of gas and oil in its main burner. However, to our knowledge, these are not available and would have to be developed specially for the IUS application. A development program would be required, and the cost would probably be excessive unless a relatively large number of installations were made. Furthermore, the dual system would be rather complex and would require separate compressors for the fuel gas.

An alternative approach for an IUS application is one analogous to the fumigation of diesel engine. That is, introduction of the fuel gas into the air before the compressor. As long as the mixture is below the flammable limits (at the local conditions existing in the compressor), no problems should be encountered. As in the case of the fumigated diesel, this system would be a very simple and low cost one from a hardware standpoint. However, to our knowledge, no one has tried this approach.

As a rough approximation, the gas turbine engine requires sufficient fuel to maintain a constant lower heating value per unit volume of combustion products. This is because turbine inlet temperature limits the firing rate to values well below stoichiometric. Therefore, any increase in volume of fuel required with a dilute fuel such as the fixed bed gasifier product, is essentially completely offset by a corresponding reduction in the volume of air. Thus, increased compressor work required to compress a high volume fuel is offset by reduced compressor work required to pump a correspondingly lower air flow.

As a result, there is no fundamental disadvantage or efficiency loss involved in burning a more dilute fuel in a gas turbine, provided the flow match of the compressor and turbine can be optimized for the particular fuel. However, in practice this may cause some complications because of the limitations of available gas turbine hardware. Most gas turbines are

designed for relatively low mass flow fuels. Since the fuel gas must be compressed separately from the engine compressor, this means that turbine mass flow will be larger than the compressor mass flow, and this mismatch will increase as the fuel Btu per unit volume goes down. This would not be a problem if there were enough design flexibility to allow matching of turbine and compressor for the particular flows. However, this might not be possible with some engines from some engine manufacturers. The most flexible gas turbine hardware probably are the heavy duty industrial machines of either European or American manufacture, and the least flexible probably are the aircraft derivative machines.

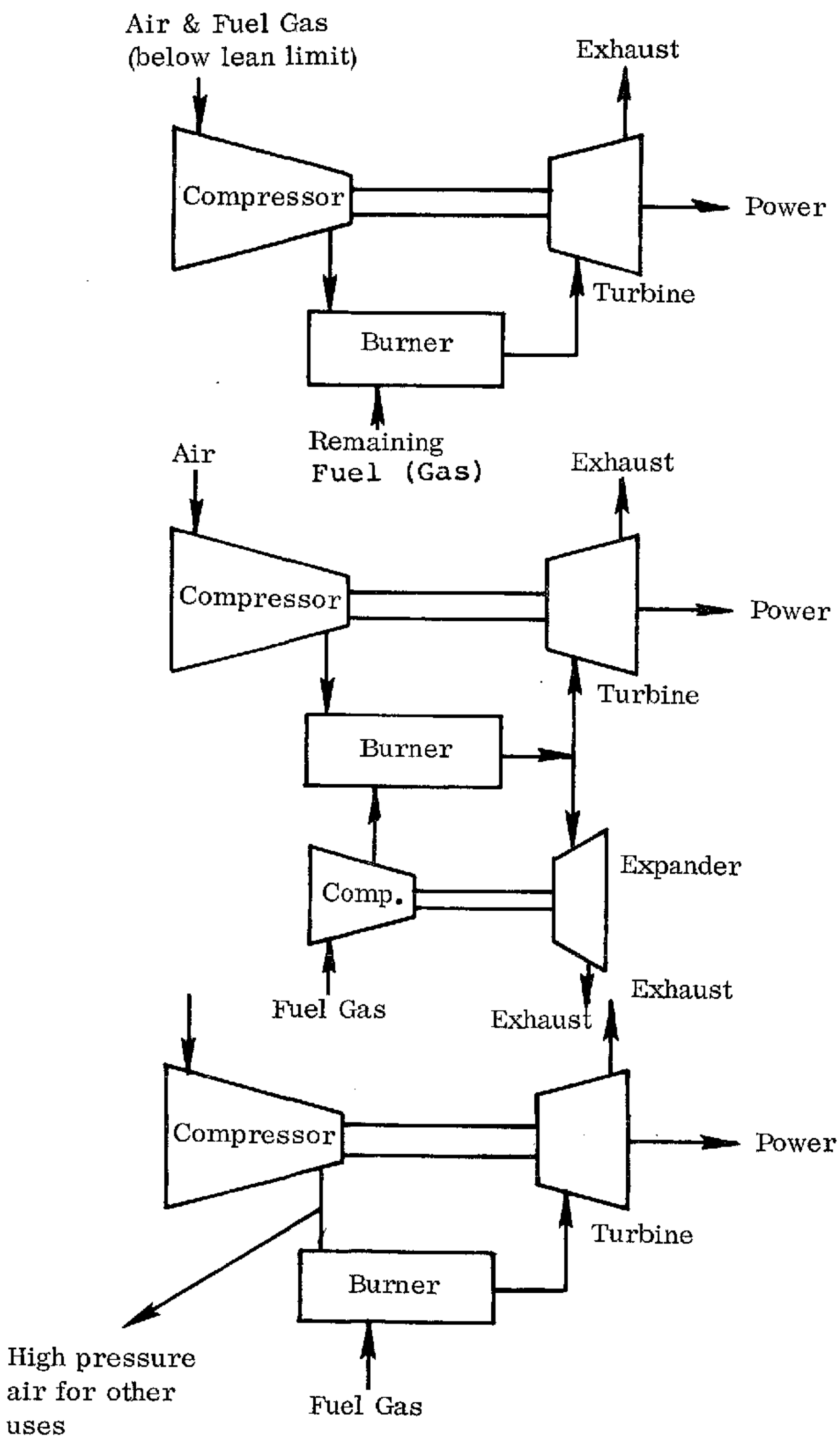
The foregoing should not be taken to mean that no suitable gas turbine hardware is presently available for low Btu service. There are a considerable number of gas turbine installations burning blast furnace gas which is considerably more dilute than the low Btu product from the fixed bed gasifier. For example, a paper presented in 1962[4] listed 16 Brown Boveri installations ranging in output from 2,500 KW to 14,000 KW. All were designed for maximum efficiency, base load operation. The only unusual problems encountered were those associated with the steel mill environment itself.

A few options that are available for cases where turbine and compressor air flow must be matched are the following. To our knowledge neither has been tried.

1. Introduce part of the fuel into the compressor inlet (analogous to fumigation) but keep it at levels below the lean limit at compressor conditions. The remaining fuel would be introduced into the burners. Some burner development would be required, and burner cooling might be a problem.
2. Bleed air flow at the turbine inlet and put it through a separate, external expander which could be used to drive the fuel gas compressor. Suitable industrial compressors and expanders are available.

A simple approach, if there is a need for compressed air, is to bleed air from the compressor exit. This would require very little change to the engine. Flow diagrams for some possible configurations are given in Figure 2.

The constraints discussed apply to both medium and low Btu fuel gases but are considerably more severe for the low Btu case. However, all major gas turbine manufacturers are showing considerable interest in developing hardware for low Btu gas firing systems to be used in conjunction with coal gasification. It is reasonable to assume that this hardware will be developed at roughly the same rate as waste pyrolysis systems. If this happens, it will be easier to obtain appropriate gas turbine hardware for the low Btu pyrolysis gas than for the medium Btu.



Gas Turbine Configuration
for Matched Compressor and Turbine Massflows

FIGURE 2

In summary, neither gas would occur significant efficiency penalty as long as suitable hardware is available. The availability of that hardware may be somewhat limited especially for the low Btu fuel gas, at least until systems are developed for coal gasification service. Since the gas production efficiency would be much greater for the low Btu gas system, the overall system efficiency would be much greater for URDC than for the Barber-Colman, even if the low Btu gas were restricted to somewhat less efficient gas turbine hardware.

If the gas turbine were part of a combined cycle with a fired rather than an unfired steam generator, then the low Btu gas would incur some efficiency penalty. However, this efficiency penalty would be smaller than the efficiency difference between a fired and an unfired combined cycle, which is very much smaller than the efficiency difference between the Barber-Colman and URDC pyrolysis systems. Therefore, the combined system efficiency must still be much greater for the URDC fixed bed system.

<u>Boilers, Ovens and Furnaces</u> - At a given temperature, the flue gas or exhaust gas loss can be related directly to LHV per ft^3 products taken at the excess air levels the particular system is running at. There is an effect of variations in exhaust gas heat capacity, but this is negligible for the purpose at hand.

Figure 3 compares the losses with the URDC and Barber-Colman gases to the loss that would be obtained firing natural gas at

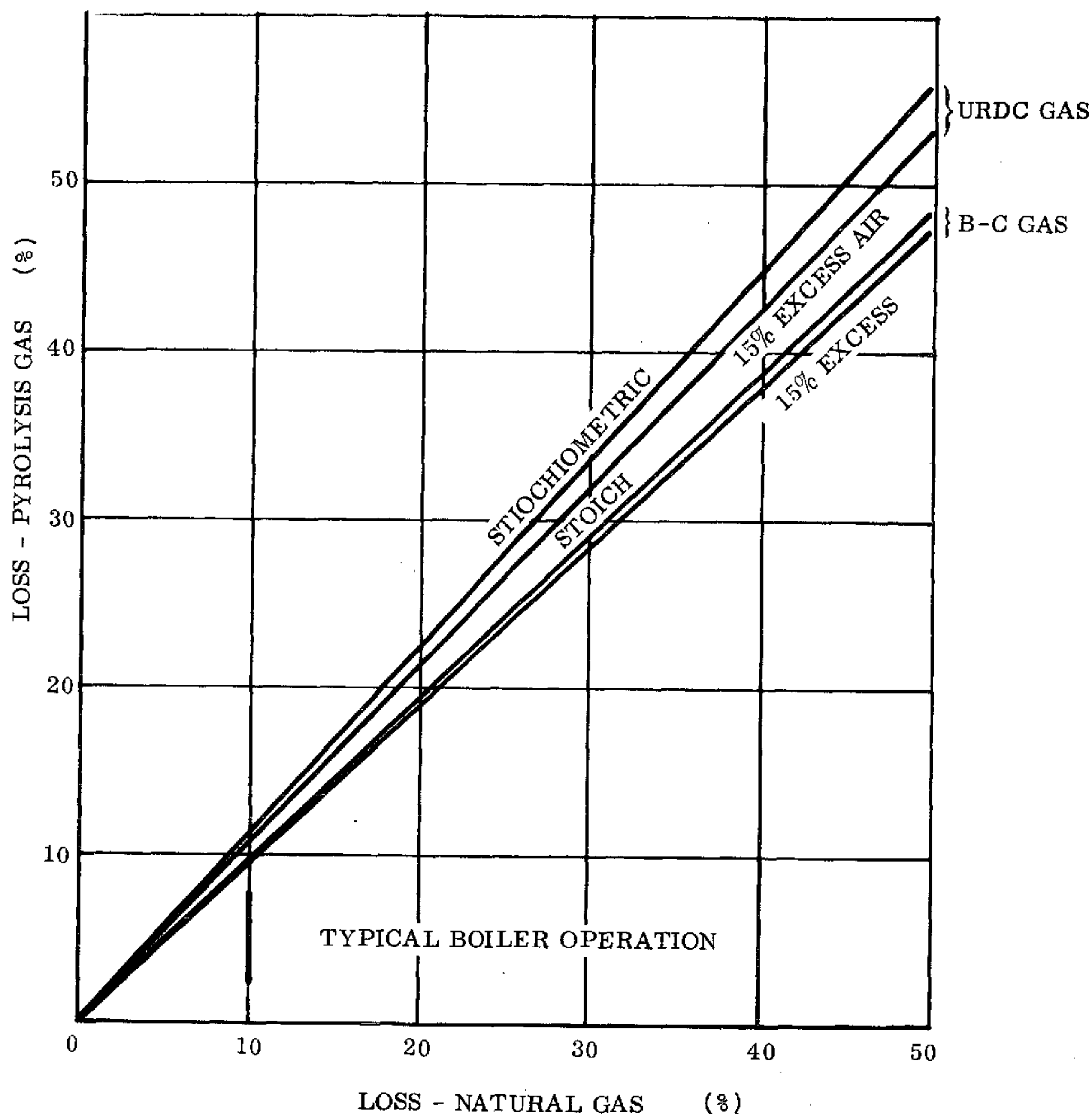


FIGURE 3

FLUE GAS OR EXHAUST GAS LOSS WITH VARIOUS FUELS AND THE SAME EXIT TEMP. VOLUMETRIC C_p's ASSUMED THE SAME FOR ALL EXHAUST STREAMS

the same exhaust temperature. The Barber-Colman product gives slightly better performance than natural gas, while the air gasifier product gives slightly poorer performance. However, the differences are very small (on the order of 1% for typical boiler conditions) unless the loss is high. (High losses correspond to high exhaust temperatures.)

Fuel Gas Rating Parameters - No single parameter is a valid across-the-board measure of a fuel gas's performance. For example, fuel gas plumbing size and pumping power is related to the lower heating value per cubic foot of fuel gas, while the flame temperature is related to the lower heating value per cubic foot of combustion products. Therefore, some parameters have been developed to compare the different facets of fuel gas performance. Results have been tabulated in Table 1 for the Barber-Colman gas, the URDC gas, and some other reference fuels.

Hamilton Standard
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TABLE 1
FUEL GAS RATING PARAMETERS

Parameter	Measure Of:	Condition	Values For: Blast Furnace	URDC	Barber-Colman	Digester Gas	Natural Gas
LHV/Ft^3 Fuel Gas	Pipeline Size; Pumping Power		92	150	449	592	911
LHV/Ft^3 Mixture	Mixture Manifold Size and Maximum Input to IC Engine	Stoichiometric 15% Excess Air	55 52	70 65	86 77	82 73	87 76
LHV/Ft^3 Products	Flame Temperature and Relative Flue Gas or Exhaust Gas Loss	Stoichiometric 15% Excess Air	60 56	78 72	90 80	82 73	87 76

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APPENDIX F2

TEST OF AN OIL FIRED DIESEL WITH INLET AIR PYROLYSIS GAS FUMIGATION

F2

TEST OF AN OIL FIRED DIESEL WITH INLET AIR PYROLYSIS GAS FUMIGATION

Introduction

In the conduct of Hamilton Standard's Pyrolysis System Evaluation Study for the NASA, it became evident that utilization of the pyrolysis gas energy by aspirating it into the air inlet (fumigation) of the Integrated Utility System's (IUS) oil fired diesel might be the most desirable means of using this gas energy. The amount of pyrolysis gas energy available would vary from zero to about 25% of the diesel prime mover's energy requirement depending on the pyrolysis waste processing rate and the electrical demand. If this fumigation technique were feasible, it would have the least capital cost effect on an IUS using a Pyrolysis System for energy recovery from refuse.

The literature has indicated that fumigation is feasible and actually may have a beneficial effect on engine efficiency, noise reduction and running smoothness. The literature, however, only discusses fumigation with liquid fuel vapors and it can only be speculated that gaseous fumigation fuels might have the same effect.

In order to gain first hand experience with the possibility of using the pyrolysis gas by fumigation, Hamilton Standard undertook a first step test program on one of its own standby diesel generator units. This test program and results are discussed below.

Conclusions

The following conclusions were reached as a result of the pyrolysis gas fumigation test program:

- Fumigation is a feasible means of utilizing the pyrolysis gas energy.
- An average utilization efficiency of the three gases used in the test program was 53.7%. (With changes in engine timing and valve overlap (scavenging air) this efficiency can be expected to increase. Gas energy carried through the engine due to scavenging will be recovered as high grade heat in an IUS.)
- There was no difference in utilization efficiency of the three different gases.
- There was no audible noise change in the engine or visible change in engine smoke when the gas was added.
- A dual fuel engine would be expected to recover nearly 100% of the energy from each of the gases tested.

Recommendations

The fumigation tests conducted by Hamilton Standard in this test program were only of a feasibility investigation nature and certainly only a first step in the complete testing which should be conducted. It is recommended, therefore, that a pyrolysis gas fumigation test program be undertaken to achieve the following objectives:

- Determine optimum valve overlap and fuel oil injection timing
- Define control requirements on fumigation gas flow.

- Determine the effect on performance with intercooling after the turbocharger.
- Determine maximum fumigation gas input.
- Verify long term operation even though no engine deterioration due to fumigation is expected.
- Conduct an investigation of pyrolysis gases in dual fuel engines.

Discussion

The fumigation test program was conducted on a Cummins Diesel Generator Set, Model NT-270-GS. The specifications for the generator set are included in Attachment 1. The Test Plan is included in Attachment 2. The fumigation gas was aspirated into the air intake down stream of the air cleaner into the 1/2 inch pipe fitting which is provided on the engine. The gas flow was manually controlled. For a permanent installation, automatic shutoff of the gas flow would be required when the engine stopped or the load level of the engine was low enough that there would be danger of the engine over speeding due to the fumigation gas input energy. The gas flow would also have to be restricted to an energy level consistent with this low load cutoff point.

During the test program, the generator set was run at a constant resistive load of approximately 88 KVA. For all tests, the time required to consume four pounds of fuel oil was recorded, and, generally, 16 pounds of fuel oil were consumed during a test run. The scale used was graduated in one one-hundredth pound increments. A five gallon container of fuel oil was placed on the

scale. The scale was set at a weight just below the weight of the fuel oil and container and when the scale balanced, the time was noted, the appropriate fumigation gas flow was set (except when the engine fuel oil consumption calibration runs were made), and the test was underway. At each four pounds of fuel oil consumption, when the scale balanced, the time was noted. The fumigation gas was controlled at a constant flow and turned off at the last fuel oil increment when the scale balanced. The fumigation gas flow reading was used only for setting an approximate gaseous energy input rate and not used in performance calculations. It was believed considerably more accurate to weigh, with the same scale used to obtain the fuel oil weight, the gas bottles before and after test.

Three different calibration runs were made on the engine during the test program. Before these tests and also before the fumigation tests, the engine was brought to normal operating temperature. The test log sheets and gas bottle gas certifications are included in Attachment 3. The performance results of the tests are shown in Table 1. In order to determine the performance contribution of the fumigation gas, the average lower heating value BTU's per minute of fuel oil consumed during all three calibration runs was used as a baseline. It can be seen that the input energy levels do not completely agree with the test plan. This disagreement resulted from an inability to predetermine the proper gas flow meter reading due to the

TABLE 1

FUMIGATION TEST RESULTS

Gas	% Gas Energy Added	% Oil Energy Saved	% Gas Utilization Efficiency	% Expected Energy Saved	Delta Actual Versus Expected
#1	5.4	2.6	47.9	2.9	+ .3
#1	5.4	4.7	86.3	2.9	+ 1.8
#1	14.5	7.0	47.9	7.8	- .8
#1	10.9	6.2	56.9	5.9	+ .3
#1	60.2	32.7	54.4	32.0	- .7
#2	6.5	2.5	38.5	3.5	- 1.0
#2	5.5	2.1	36.8	3.0	- .9
#2	22.0	15.4	69.7	11.8	+ 3.6
#2	18.6	9.4	50.6	10.0	- .6
#3	4.5	0	0	2.4	- 2.4
#3	12.7	7.2	57.0	6.8	+ .4
#3	5.8	5.7	98.8	3.1	+ 2.6
		Average =	53.7	Average	+=1.5
				Average	-=1.1

Lower Heating Value (LHV) of Fuel Oil = 18,362 Btu/Lb

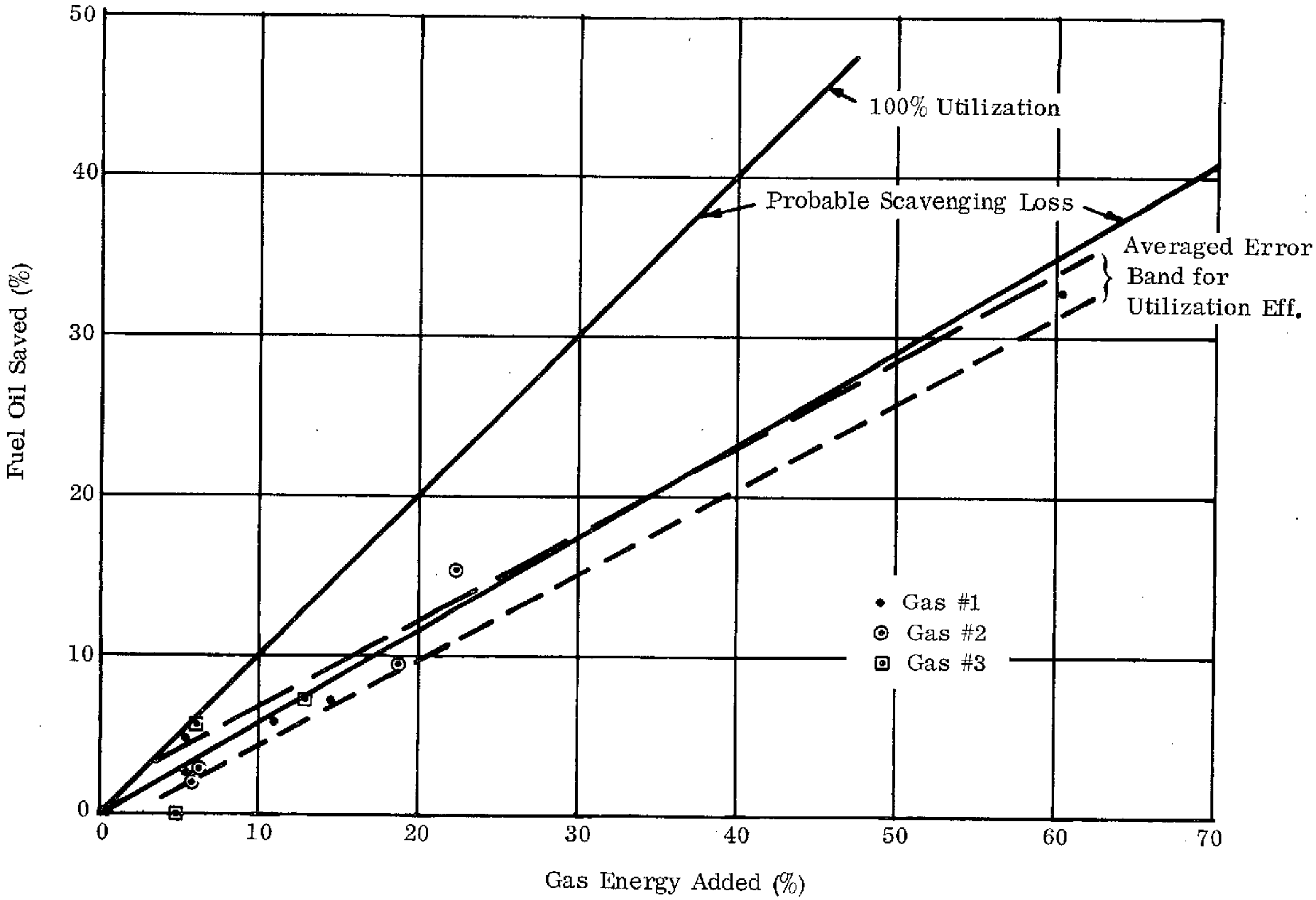
LHV of Gas #1 = 2,525 Btu/Lb

LHV of Gas #2 = 8,467 Btu/Lb

LHV of Gas #3 = 6,276 Btu/Lb

variation in gas temperature and pressure for each gas flow case. The precise energy input levels are not considered important. It was believed much more important to control a constant energy input rate during the test and to use consumed fuel oil and gas weights in order to make reasonably accurate calculations of performance. From the Table, it is seen that the average utilization efficiency was 53.7 percent of the gas energy added. It is believed that the inherent errors in the test procedure are nearly equal at any fumigation gas energy input level. As a result, the average utilization was used to calculate an expected energy saved, and this value was subtracted from what was actually observed by the difference between calibration baseline fuel oil consumption and fuel oil consumption during each particular test divided by the baseline fuel oil consumption (the percent energy saved column). The delta from expected fuel oil energy saved was averaged to get a plus and minus error band. This error band is shown on Figure 1 which also shows each test point for each fumigation gas. The engine valve overlap will limit the utilization of all of the fumigator gas since the gas in the scavenging air will burn in the exhaust and not contribute to energy output of the engine. With engine heat recovery on the exhaust, as in an IUS, this gas energy is recovered in the form of high grade heat.

From discussions with the engine supplier, it was determined that nearly all of the unused gaseous energy may have blown



FUMINGATION TEST RESULTS

FIGURE 1

through the cylinders due to scavenging. The manufacturer stated that the air flow rate at the load conditions tested was 33 pounds per minute, the effective displacement of the engine is 403 ft^3 per minute at 1,800 rpm considering a valve overlap of 72^o, the turbocharger discharge pressure is 19.2 psia, and the probable cylinder temperature is 400^{o}F. Considering a scavenging efficiency of 80% the amount of air plus gaseous fuel which could flow through the cylinder is 42% or only 58% of the fuel could be utilized.

During the testing, no changes in engine audible sound level or visible smoke output could be detected when the fumigation gas was turned on or off. The four personnel involved in the testing agreed with this conclusion. No instrumentation was used for the determination of engine noise, vibration or smoke output.

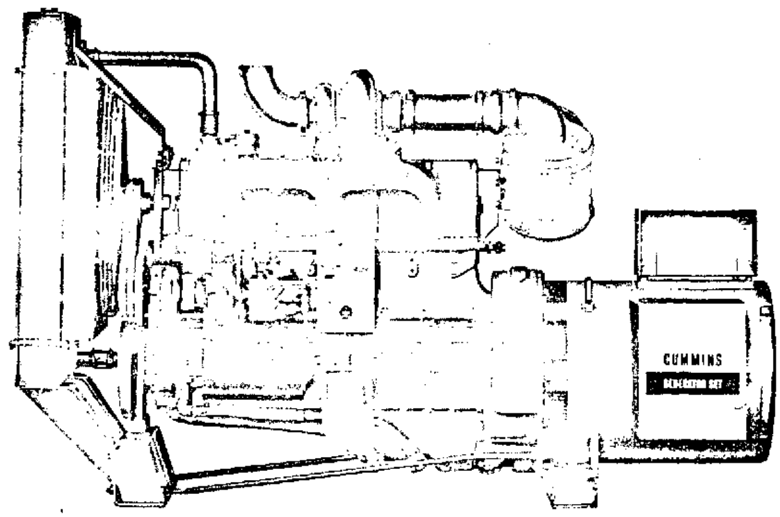
Considering that as much gaseous energy was used by the engine as was possible with the valve overlap and fuel timing, it is probable that a dual fuel engine which times the injection of the gaseous fuel would give very nearly 100% utilization of the pyrolysis gas energy.

ATTACHMENT 1

CUMMINS DIESEL GENERATOR SET

SPECIFICATIONS

Cummins Generator Set NT-270-GC



Specifications

Rated Output*	60 Hertz	50 Hertz
KW @ 0.8 PF	125	100
KVA	156	125
Governed RPM at rated frequency	1800	1500
Operating Cycles	4	
Number of Cylinders	6	
Bore and Stroke — in.	$5\frac{1}{2}$ x 6	
— mm.	140 x 152	
Piston Displacement — cu. in.	855	
— liters	14.02	
Net Weight — static generator — lbs.	4860	
— kg.	2205	
— brushless generator — lbs.	4610	
— kg.	2092	

*Applicable to the combined operating conditions up to 5000 feet above sea level and ambient temperature up to 100°F, in utility-type, prime power systems with normal load factors. In this application, it may be operated continuously, 24 hours per day, with no deration.

The generator set includes reserve capacity for conditions above the standard rating, including 10% for an aggregate of two hours in any 24 hours of operation. Additional capacity, yielding gains in performance and economic return is available to meet specific applications. Submit detailed information for factory approval.

Standard Equipment

Base Mounting: Fabricated steel cross member type.

Cleaner, Air: Dry type, mounted.

Corrosion Resistor: Mounted, replaceable element, checks rust and corrosion, controls acidity, and removes impurities from coolant.

Coupling: Positive alignment, laterally flexible, laminated steel disc, easily accessible.

Electrical Equipment — Engine: 24 volt starting motor, 24 volt 20 ampere battery charging generator, voltage regulator.

Fan: Axial blower type complete with wire guard.

Filters: Lubricating oil, full flow paper element type, mounted. Fuel, heavy duty replaceable paper element type, mounted.

Governor: Woodward hydraulic, 3% speed droop, with idle speed setting. External vernier control for engine speed adjustment.

Lifting Brackets: Adequate eye brackets provided.

Panel, Instrument: Includes ammeter, lubricating oil pressure and temperature gauges, cooling water temperature gauge, hourmeter.

Pump, Coolant: Centrifugal type.

Radiator: Heavy duty type for 100°F. ambient temperature at specified rating.

Vibration Isolators: Rubber type between unit and cross-member.

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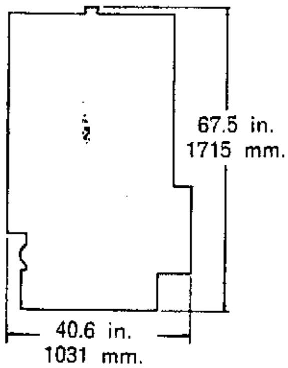
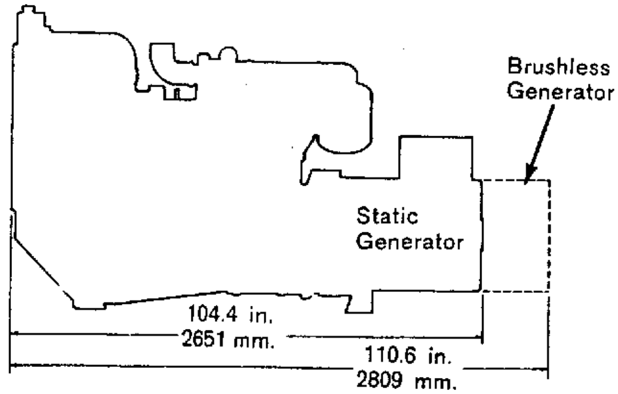
Application Data





Operating Data

Crankcase Oil Capacity	7	gal.
Coolant Capacity — engine only	5.0	gal.
— with radiator	21.1	gal.
Air for Combustion — 60 Hz	640	CFM
— 50 Hz	485	CFM
Air for Radiator Cooling — 60 Hz	14100	CFM
— 50 Hz	11700	CFM

Fuel Consumption

	60 Hertz			50 Hertz		
Load	KW	U.S. Gals/Hr.	Lbs./KW Hr.	KW	U.S. Gals/Hr.	Lbs./KW Hr.
Full	125.0	10.1	.572	100	8.1	.553
3/4	93.7	8.1	.612	75	6.3	.577
1/2	62.5	6.3	.720	50	4.8	.650
1/4	31.2	4.5	.969	25	—	—

Design Features, Engine

Bearings: Precision type, steel backed inserts. 7 main bearings, 4 1/2" diameter. Connecting Rod — 3 1/8" diameter.

Camshaft: Single camshaft controls all valve and injector movement. Induction hardened alloy steel with gear drive.

Cooler, Lubricating Oil: Tubular type, jacket water cooled.

Crankshaft: High tensile strength steel forging. Bearing journals are induction hardened. Fully counterweighted.

Cylinder Block: Alloy cast iron with removable, wet liners.

Cylinder Heads: Each head serves two cylinders. Drilled fuel supply and return lines. Corrosion resistant inserts on intake and exhaust valve seats.

Damper, Vibration: Compressed rubber type.

Fuel System: Cummins PT self adjusting system. Camshaft actuated injectors, flyball mechanical governor provides overspeed protection independent of main engine governor.

Lubrication: Force feed to all bearings, gear type pump. All lubrication lines are drilled passages, except pan to pump suction line.

Pistons: Aluminum, cam ground, with three compression and one oil ring.

Turbocharger: Cummins T-50.

Valves: Dual intake and exhaust each cylinder. Each valve 1 7/8" diameter. Heat and corrosion resistant face on exhaust valve.

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Cummins Engine Company, Inc.
Columbus, Indiana, U. S. A. 47201

Design Features, Generator

Construction: Built to recommended standard of N.E.M.A. MG2-1967, Section 22, revised January 1968 and B.S. 2613:1957 Revised March 1964.

Bearing: Single row ball, double shielded, greasible.

Cooling: Ventilating fan part of drive assembly.

Damper Windings: Continuous amortisseur windings for parallel operation.

Exciter: Offered in either solid state static exciter design or brushless rotating exciter design.

Insulation: Class F.

Main Frame: Cast iron construction.

Rotor: Dynamically balanced 4 pole to tolerate up to 25% overspeeding.

Stator: 6 coil, 12 lead permits multiplicity of 3 phase Y or Δ and single phase connections.

Temperature Rise: 70°C. or less at 40°C. ambient temperature, by thermometer.

Voltage Regulator: Transistor amplifier and silicon controlled rectifier type ±1% regulation maintained from no load to full load. Modular construction. Voltage range adjustable 15%.

Voltages Available:

	3Y	4Y	3Δ
60 Hz	208 to 240	120/208 to 138/240	120 to 138
	416 to 480	240/416 to 277/480	240 to 270
50 Hz	173 to 208	100/173 to 120/208	100 to 120
	346 to 416	200/346 to 240/416	200 to 240

Engine Tested

Generator Set Specifications

	60 Hertz		50 Hertz	
	Prime Power	Standby Power	Prime Power	Standby Power
Model	NT-270-GC	NT-270-GS	NT-270-GC	NT-270-GS
KW Rating at 0.8 P.F.	125	150	100	125
Overload Capacity	10%	—	10%	—
Weight: Static Generator	4860 lbs.	4860 lbs.	2205 Kg	2205 Kg
Brushless Generator	4610 lbs.	4610 lbs.	2092 Kg	2092 Kg

Engine Specifications

Engine Type (6 cylinder in line Diesel 4 cycle Turbocharged)

Displacement	855 Cu. in. (773.6 After Intake Closes)		14.02 Liters	
Bore and Stroke	5½ in. x 6 in.		140 mm x 152 mm	
Compression Ratio	14.1:1		14.1:1	
Engine Speed	1800 RPM	1800 RPM	1500 RPM	1500 RPM
Piston Speed	1800 FPM	1800 FPM	7.62 MPS	7.62 MPS
Brake Horsepower Available (85°F, 500 Ft.)	238 HP	238 HP	204 HP	204 HP
Brake Mean Effective Pressure (BMEP at rated KW output): With Fan	101.7 PSI	121.9 PSI	6.85 Kg/Sq Cm	8.55 Kg/Sq Cm
Without Fan	98.1 PSI	118.3 PSI	6.67 Kg/Sq Cm	8.38 Kg/Sq Cm

Engine Lube Oil System

	60 Hertz	50 Hertz
Oil Pan Capacity (Standard Pan): High Level	7 Gal	26.5 Liters
Low Level	4 Gal	15.2 Liters
Maximum Angularity for Sustained Operation		
Generator End Down	20°	20°
Front Support End Down	15°	15°
Side to Side	35°	35°

Lube Oil Specifications

Oil should meet quality requirements of Military Spec: MIL-L-2104B/MIL-L-45199B.
SAE 10W when ambient temperature is between 0° and 32°F.
SAE 20W when ambient temperature is between 32°F and 90°F.
SAE 30W when ambient temperature is above 90°F.

Engine Electrical System

DC System (Negative Ground) with 24 Volt, 20 Amp. generator, voltage regulator, and 24 Volt Starter.

	0° to 32°F	Above 32°F
Minimum Battery Capacity	260 AH	170 AH

Intake Air Requirements

Air Consumption (at rated load)	~~640~~ 555 CFM	640 CFM	13,735 Lit/Min	13,735 Lit/Min
Maximum Restriction at Intake Manifold				
(clean element)	12 in. H_2O	12 in. H_2O	30.48 Cm H_2O	30.48 Cm H_2O
(used element)	25 in. H_2O	25 in. H_2O	63.5 Cm H_2O	63.5 Cm H_2O

Cooling System

(centrifugal pump type with thermostatically controlled bypass)

Heat Rejection to Cooling Water (Dry Exhaust)	5950 BTU/Min	7020 BTU/Min	18,310 Cal/Sec	22,680 Cal/Sec
Cooling Water Flow	86 GPM	86 GPM	272 Lit/Min	272 Lit/Min
Coolant Capacity with Radiator	21.1 Gal	21.1 Gal	79.9 Liters	79.9 Liters
Heat Radiated to Room Ambient Air (Engine & Generator)	3490 BTU/Min	3490 BTU/Min	12,560 Cal/Sec	12,560 Cal/Sec
Raw Water Flow to Heat Exchanger at 80°F	34 GPM	34 GPM	129 Lit/Min	129 Lit/Min
Heat Exchanger Maximum Allowable Pressure	75 PSIG	75 PSIG	5.2 Kg/Sq Cm	5.2 Kg/Sq Cm
Cooling Fan Delivery	14,100 CFM	14,100 CFM	333,000 Lit/Min	333,000 Lit/Min
Minimum Air Vent Cross Section for Enclosed Installations (with radiator & blower fan)				
Combustion and Cooling Air Inlet	14.0 Ft^2	14.0 Ft^2	13,000 Sq Cm	13,000 Sq Cm
Cooling Air Discharge	9.5 Ft^2	9.5 Ft^2	8825 Sq Cm	8825 Sq Cm

Fuel System

	60 Hertz		50 Hertz	
	Prime Power	Standby Power	Prime Power	Standby Power
Fuel Consumption (with 19,250 BTU/Lb.)				
100% Load	10.1 Gal/hr	12.1 Gal/hr	29.5 Lit/hr	36.4 Lit/hr
75% Load	8.1 Gal/hr	9.3 Gal/hr	23.3 Lit/hr	28.0 Lit/hr
50% Load	6.3 Gal/hr	7.0 Gal/hr	17.7 Lit/hr	20.4 Lit/hr
25% Load	4.3 Gal/hr	4.9 Gal/hr	11.6 Lit/hr	13.7 Lit/hr
Approximate Fuel Flow to Pump at Rated Load	55 Gal/hr	55 Gal/hr	190 Lit/hr	190 Lit/hr
Maximum Fuel Inlet Restriction	4.5 Ft H_2O	4.5 Ft H_2O	137 Cm H_2O	137 Cm H_2O
Minimum Size Fuel Oil Supply Line	½ in. I.D.	½ in. I.D.	1.27 Cm I.D.	1.27 Cm I.D.
Minimum Size Fuel Oil Return Line	13/32 in. I.D.	13/32 in. I.D.	1.03 Cm I.D.	1.03 Cm I.D.

Note: A fuel float tank is required where fuel level in supply tank is above injector return fitting.

Generator

	Static	Brushless
Frame Size	500-4	440
Leads	12	12
Type	Revolving Field	Revolving Field
Exciter Type	Static—Solid State	Brushless Rotary
Voltage Regulator	Static—Solid State	Solid State
Insulation	Class F	Class F
Number of Bearings	One	One
Coupling	Flexible Disc	Flexible Disc
Rotor Balancing	25% Overspeed	25% Overspeed
Synchronous Reactance (Xd) 480V	1.88	2.20
Transient Reactance (X′d) 480V	0.272	0.141
Sub Transient Reactance (X″d) 480V	0.164	0.103
Short Circuit Ratio 480V	0.667	0.680
Test Voltage: Rotor	1500	1500
Stator	2000	2000
Wave Form Deviation No Load (480V)	2.44%	1.86%
Telephone Interference Factor—No Load (KV. Y TIF) (480V)	56.1	<150

	Static				Brushless			
Voltage Regulation	Prime Power		Standby		Prime Power		Standby	
	60 Hz	50 Hz	60 Hz	50 Hz	60 Hz	50 Hz	60 Hz	50 Hz
Steady State	±0.25%	±0.25%	±0.25%	±0.25%	±0.25%	±0.25%	±0.25%	±0.25%
No Load to Full Load	±1.0%	±1.0%	±1.0%	±1.0%	±1.0%	±1.0%	±1.0%	±1.0%
Recovery Time	1.0 Sec	1.0 Sec	1.0 Sec	1.0 Sec	1.0 Sec	1.0 Sec	1.0 Sec	1.0 Sec
Motor Starting Ability (Code F Motors) No preload—30% voltage dip 460 V—60 Hz 400 V—50 Hz	79 HP	66 HP	79 HP	66 HP	100 HP	80 HP	100 HP	80 HP
KW Pickup in One Step (.8 Power Factor)	125	100	150	125	125	100	150	125
Stator Temperature Rise Above 40°C Ambient (240 or 480—60 Hz by thermometer 208 or 416—50 Hz)	50°C	50°C	70°C	70°C	50°C	50°C	50°C	50°C

Amortisseur Windings— Output Voltage and Range Adjustment		Low Range		High Range		Low Range		High Range	
		60 Hz	50 Hz	60 Hz	50 Hz	60 Hz	50 Hz	60 Hz	50 Hz
Connection	3 △	120-138	100-120	240-277	200-240	120-138	100-120	240-277	200-240
	4 Y	120/208 to 138/240	100/173 to 120/208	240/416 to 277/480	200/346 to 240/416	120/208 to 138/240	100/173 to 120/208	240/416 to 277/480	200/346 to 240/416
	3 Y	208-240	173-208	416-480	346-416	208-240	173-208	416-480	346-416

References (Cummins Bulletin Numbers)

	Static		Brushless	
	Prime Power	Standby	Prime Power	Standby
Cummins Generator Set Specification Sheets	950651	950663	950651	950663
Installation Diagram—Radiator Cooled	203896	203896	208896	203896
Installation Diagram—Heat Exchanger Cooled	204307	204307	204307	204307
Service Manual	983600B	983600B	983679	983679
Parts Catalog	966967	966967	966967	966967
Wiring Diagram	196812	196812	196812	196812

ATTACHMENT 2

TEST PLAN

FOR

TEST OF AN OIL FIRED DIESEL

WITH INLET AIR PYROLYSIS GAS FUMIGATION

TEST OF AN OIL FIRED DIESEL WITH INLET AIR PYROLYSIS GAS FUMIGATION

Objective

Determine the reduction in oil consumption by fumigating pyrolysis gas into the inlet air of an oil fired multi-cylindered diesel engine.

Discussion

Hamilton Standard is conducting a study program on the potential utilization in an integrated utility system such as the MIUS, of two different solid waste disposal techniques employing pyrolysis for thermally reforming the waste into fuel gas. The most desirable way of using the energy of this fuel gas is to burn it in the electrical generation prime mover. It is a study ground rule that the prime mover be an oil fired diesel. The gas energy represents from 5 to 25% of the total engine energy input requirement. If this gas can be fumigated into the engine air inlet and reduce the oil consumption of the engine, it would probably be the most efficient use of this otherwise wasted energy. Considering the total air flow into the engine, the 5 to 25% gas energy would represent a fuel percentage of 15 to 70% of the lean combustible limit, and no preignition will occur.

Test Plan

With reference to the attached schematic, premixed gas will be used to represent the three different compositions of gas to be

tested. These compositions are given below:

Component % By Volume	Gas 1	Gas 2	Gas 3
CO_2	3.5	19.9	47.0
N_2	48.2	0.0	0.0
CH_4	1.1	16.2	53.0
CO	30.1	19.1	0.0
H_2	16.4	35.7	0.0
C_2H_4	.6	9.1	0.0
Btu/Ft^3 Gas (LHV)	161	446	483
Btu/Ft^3 Air + Gas Mix.	70	86	79.8

The gases will be regulated to a low pressure sufficient to obtain the necessary flow through a flow meter used to measure the gas being supplied to the engine air. An emergency solenoid shutoff valve will be placed in the line which can shut off gas flow instantly. An oil fuel consumption measuring technique is required preferably a weight measurement. A load bank capable of applying between 50 and 80% load to the prime mover will be required.

With the engine at a fixed constant load, the fuel oil consumption shall be measured for each of the following approximately one half hour tests:

Test 1 - Measure oil consumption without fumigation.

Test 2 - With gas #1, add 5% equivalent energy in fumigation gas as determined from test #1 and measure fuel oil consumption.

<u>Tests 3 to 11</u> - Repeat test #2 at 15% and 25% on gas #1 and repeat test #2 and these higher percentage gas flows for gases #2 and #3.

<u>Test 12</u> - Repeat test #1.

During all tests, check and maintain gas flows and electrical load.

During any test, if any abnormality occurs in engine performance, shut off gas flow immediately.

ATTACHMENT 3

TEST LOG SHEETS AND

GAS BOTTLE GAS CERTIFICATIONS

HSF-175.1A 1/66

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION
WINDSOR LOCKS, CONNECTICUT 06096

SPACE & LIFE SYSTEMS LABORATORY
LOG OF TEST

TYPE OF TEST: GAS FUMIGATION - 5% GAS I
TEST ENGINEER: A. RYAN
NAME OF RIG: STANDBY DIESEL - WASTE TREATMENT
PROJECT & ENG. ORDER NO.

SHEET 1 OF 1 DATE 11-13-74
TEST PLAN NO.
MODEL NO.
PART NO.
SERIAL NO.
OPERATORS Allen Ryan 11/13/74

TIME	TIME UNIT SEC	FUEL USED #		GAS FLOW %		VOLTAGE VOLTS		CURRENT AMPS		SET POWER KW		GAS PRESS PSI		GAS TEMP °F		ENG TEMP °F		GAS BOTTLE 1 #	2	3	4	
1425	0	0		100		470		108		84		15.5		100		170		135.39				
1430	303	4		100		470		108		84		15.5		100		175						
1435	597	8		100		470		108		84		15.5		100		175						
1440	892	12		100		470		108		84		15.5		100		175						
1445	1180	16		100		470		108		84		15.5		100		175		128.93				

F2-19

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REMARKS: POWER FACTOR 1.0, FREQUENCY 60HZ   BOTTLE PRESS. 450 PSI END

78479

HSF-178.1A 1/66

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION
WINDSOR LOCKS, CONNECTICUT 06096

SPACE & LIFE SYSTEMS LABORATORY

LOG OF TEST

TYPE OF TEST: GAS FUMIGATION - 5%

TEST ENGINEER: A. RYAN

NAME OF RIG: STANDBY DIESEL-WASTE TR

PROJECT & ENG. ORDER NO.

SHEET 1 OF 1 DATE 11-18-74

TEST PLAN NO.

MODEL NO. GAS #1

PART NO.

SERIAL NO.

OPERATORS Allen Elynn

TIME	TIME LINE	FUEL USED	GAS FLOW	VOLTAGE	CURRENT	SET POWER	GAS PRESS	GAS TEMP	ENG TEMP		GAS BOTTLES	
	SEC.	#	%	VOLTS	AMPS	KW	PSIA	°F	°F			
											NO.	216
1035	0	0	100	470	108	84	15.5		175	76		
											INITIAL WGT	132.12
1040	309	4	100	470	108	84	15.5		178	59		
											FINAL WGT.	125.51
1045	609	8	100	470	108	84	15.5		180	54		
1050	907	12	100	470	108	84	15.5		182	60		
1055	1206	16	100	470	108	84	15.5		182	60		

REMARKS: POWER FACTOR 1.0. FREQUENCY 60 HZ

78384

F2-20

HSF-175.1A 1/66

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION
WINDSOR LOCKS, CONNECTICUT 06096

SPACE & LIFE SYSTEMS LABORATORY
LOG OF TEST

TYPE OF TEST: GAS FUMIGATION GAS #1
TEST ENGINEER: A. RYAN
NAME OF RIG: STANDBY DIESEL-WASTE TREATMENT
PROJECT & ENG. ORDER NO.

SHEET 1 OF 1 DATE 11-14-74
TEST PLAN NO. 159/3
~~MODEL NO.~~ GAS BOTTLE M
PART NO. 1C 4221
SERIAL NO. 1C 2031
OPERATORS

TIME	TIME UNITS SEC	FUEL USED LBS	GAS FLOW %	VOLTS VAC	AMB	PWR OUT KW	GAS PRESS PSIA	ENG TEMP °F	GAS TEMP °F	GAS NUMBER		
										GAS BOTTLE	1A 2616	1C 2630
1514	0	0	26	470	107	84	17.7	180	* ~~109~~	INITIAL WT.	131.27	131.90
1519	314	4	26	470	107	84	17.7	180	~~109~~	FINAL WT.	NOT USED	
1524	621	8	26	470	108	84	17.7	185	~~112~~	GAS BOTTLE	1C 2831	1C 4221
										INITIAL WT.	132.69	131.90
1529	930	12	26	471	108	84	17.7	185	~~117~~			
										FINAL WT.	125.87	125.16
1534	1226	16	26	471	108	84	17.7	185	~~117~~			

F2-21

GAS F/R I.D. F/R-1-G-10/83

REMARKS:
* Temp. readout in error. Temp was ≃ 40-50°F. START ENGINE 1422

78482

HSF-175.1A 1/66

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION
WINDSOR LOCKS, CONNECTICUT 06096

SPACE & LIFE SYSTEMS LABORATORY

LOG OF TEST

TYPE OF TEST: GAS FUMIGATION GAS #1
TEST ENGINEER: A. RYAN
NAME OF RIG: STANDBY DIESEL-WASTE TR
PROJECT & ENG. ORDER NO.

SHEET 1 OF 1 DATE 11-15-74
TEST PLAN NO.
MODEL NO. 1590
PART NO.
SERIAL NO.
OPERATORS

TIME	TIME UNIT	FUEL USED	GAS FLOW	VOLTAGE	CURRENT	PWR SET	GAS F/R	GAS TEMP	ENG TEMP			GAS 1	BOTTLES 2	3	4
	SEC.	#	%	VOLTS	AMPS	KW	%	°F	°F						
			PRES PSIA								No.	2616	2030	6080	
0945	0	0	19	470	108	84	32	135	175				:		
										INIT	WET	132.27	131.40	134.57	
0950	513	4	19.5	471	108	84	33	39	175						
										FINAL	WET.	132.12	123.49	126.73	
0955	623	8	19.5	471	108	84	33	39	175						
1000	931	12	19.5	471	108	84	33	42	178						
1003	1081	14	19.5	471	108	84	33	42	180						
		16													

GAS #1

F/R SETTING CHANGED AT 0947 to 33% & 19.5 psia
T/C LEADS CHANGED AT 0948

REMARKS: POWER FACTOR 1.0 FREQUENCY 60 HZ

F2-22

78488

HSF-175.1A 1/66

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION
WINDSOR LOCKS, CONNECTICUT 06096

SPACE & LIFE SYSTEMS LABORATORY
LOG OF TEST

TYPE OF TEST: GAS FUMIGATION Gas #1
TEST ENGINEER: A-RYAN
NAME OF RIG: STANDBY DIESEL-WASTE TREATMT
PROJECT & ENG. ORDER NO.

SHEET 1 OF 1 DATE 11/14/72
TEST PLAN NO.
MODEL NO. GAS BOTTLE Nos
PART NO. IC1001, IC2029
SERIAL NO. IC1814, IC1352
OPERATORS

TIME	TIME UNITS	FUEL USED		GAS FLOW		VOLTS		AMPS		PWR SET		GAS PRESS	GAS TEMP	ENG TEMP
	SEC	LBS		%		VAC				KW		PSIA	°F	°F
1136	0	0		6		470		107		84		55	~~80~~	180
	224	2				470		107		84	↓			180
	427	4				470		107		84		65		180
		8												
		12												
		16												

GAS No. 1

GAS BOTTLE 1C1001
INITIAL WT: 130.89
FINAL WT. 122.23

GAS BOTTLE 1C1814
INITIAL WT. 132.80
FINAL WT. 124.17

GAS BOTTLE IC2029
INITIAL WT 132.30
FINAL 133.18

GAS BOTTLE 1C1352
INITIAL 132.81
FINAL 124.23

REMARKS: POWER FACTOR 1.0 FREQUENCY 60Hz

F2-23

78483

HSF-175.1A 1/66

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION
WINDSOR LOCKS, CONNECTICUT 06096

SPACE & LIFE SYSTEMS LABORATORY

LOG OF TEST

TYPE OF TEST: GAS FUMIGATION GAS #2
TEST ENGINEER: A. RYAN
NAME OF RIG: STANDBY DIESEL - WASTE TR.
PROJECT & ENG. ORDER NO.

SHEET 1 OF 1 DATE 11-15-74
TEST PLAN NO.
MODEL NO. 5%
PART NO.
SERIAL NO.
OPERATORS

TIME	TIME UNITS	FUEL USED	GAS FLOW	VOLTAGE	CURRENT	PWR SET	GAS PRESS	GAS TEMP	ENG TEMP		GAS BOTTLES 1	2	3	4
	SEC	#	%	VOLTS	AMPS	KW	PSIG	°F	°F					
										NO.	3268			
1048	0	0	41	471	108	84	14.8	86	175					
										INI WGT	134.01			
1053	299	4	41	471	108	84	14.8	66	175					
										FINAL WGT	131.95			
1058	596	8	41	471	108	84	14.8	66	175					
1103	889	12	41	471	108	84	14.8	64	175					
1108	1175	16	41	471	108	84	14.8	64	175					

REMARKS: POWER FACTOR 1.0 FREQUENCY 60 HZ

F2-24

78487

HSF-175.1A 1/66

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION
WINDSOR LOCKS, CONNECTICUT 06096

SPACE & LIFE SYSTEMS LABORATORY
LOG OF TEST

TYPE OF TEST: GAS FUMIGATION GAS #2
TEST ENGINEER: A. RYAN
NAME OF RIG: STAND BY DIESEL-WASTE TR.
PROJECT & ENG. ORDER NO.

SHEET 1 OF 1 DATE 11-15-74
TEST PLAN NO.
MODEL NO. 5%
PART NO.
SERIAL NO.
OPERATORS

TIME	TIME UNITS	FUEL USED	GAS FLOW	VOLTAGE	CURRENT	SET POWER	GAS PRES.	GAS TEMP	ENG TEMP	GAS BOTTLES			
	SEC.	#	%	VOLTS	AMPS	KW	PSIA	°F	°F	1	2	3	4
										No.	3328		
1116	0	0	41	470	108	84	14.9	92	180				
										INI WGT	126.60		
1121	296	4	41	470	108	84	14.9	76	180				
										FINAL WGT	124.30		
1126	587	8	41	471	108	84	14.9	75	180				
1131	887	12	41	471	108	84	14.9	70	180				
1136	1179	16	41	471	108	84	14.9	73	182				

REMARKS: POWER FACTOR 1.0. FREQUENCY 60 HZ

F2-25

78383

HSF-175.1A 1/66

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION
WINDSOR LOCKS, CONNECTICUT 06096

SPACE & LIFE SYSTEMS LABORATORY

LOG OF TEST

TYPE OF TEST: GAS FUMIGATION GAS #2
TEST ENGINEER: A. RYAN
NAME OF RIG: STANDBY DIESEL-WASTE TR.
PROJECT & ENG. ORDER NO.:

SHEET 1 OF 1 DATE 11-15-74
TEST PLAN NO.:
MODEL NO.: 15%
PART NO.:
SERIAL NO.:
OPERATORS:

TIME	TIME UNITS	FUEL USED	GAS FLOW	VOLTAGE	CURRENT	PWR SET	GAS PRES	GAS TEMP	ENG TEMP		GAS BOTTLES 1	2	3	4
	SEC.	#	%	VOLTS	AMPS	KW	PSIA	°F	°F					
										No.	3268		3328	
1131	0	0	15	471	108	84	15.6	73	175					
										INI WET	131.95		126.65	
1136	314	4	15	471	108	84	15.6	45	175					
										FINAL WET	127.56		126.60	
1141	634	8	15	471	108	84	15.6	43	175					
1144	793	10	15	471	108	84	15.6	44	175					
		12												
		16												

REMARKS: POWER FACTOR 1.0 FREQUENCY 60 HZ

78486

F2-26

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HSF 175.1A 1/66

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION
WINDSOR LOCKS, CONNECTICUT 06096

SPACE & LIFE SYSTEMS LABORATORY

LOG OF TEST

TYPE OF TEST: GAS FUMIGATION – 15% Gas #2
TEST ENGINEER: A. RYAN
NAME OF RIG: STANDBY DIESEL – WASTE TREATMENT
PROJECT & ENG. ORDER NO.:

SHEET 1 OF 1 DATE 11-13-74
TEST PLAN NO.
MODEL NO.
PART NO.
SERIAL NO.
OPERATORS

TIME	TIME UNITS SEC.	FUEL USED #	GAS FLOW %	VOLTAGE VOLTS	CURRENT AMPS	SET POWER K.W	GAS PRESS PSI	GAS TEMP °F	ENG TEMP °F	GAS BOTTLE 1 #	2	3	4
1110	0	0	17.5	465	107	84	16	* ~~80~~	170	129.26			
1115	330	4	17.5	468	107	84	16	~~84~~	175				
1120	676	8	17.5	468	107	84	16	~~92~~	178				
1125	1019	12	17.5	468	107	84	16	~~95~~	180	122.48			
		16											

REMARKS: POWER FACTOR 1.0, FREQUENCY 60 Hz. * Temp not correct. Temp ≈ 40–50°F
FUEL WGT START 35.0

78478

F2-27

HSF-175.1A 1/66

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION
WINDSOR LOCKS, CONNECTICUT 06096

SPACE & LIFE SYSTEMS LABORATORY

LOG OF TEST

TYPE OF TEST: GAS FUMIGATION TEST - GR#3
TEST ENGINEER: A. RYAN
NAME OF RIG: TRANSIT DIESEL-WASTE TREATMENT
PROJECT & ENG. ORDER NO.:

SHEET 1 OF 1 DATE 11-12-74
TEST PLAN NO. $CO_2 + CH_4$
MODEL NO.
PART NO.
SERIAL NO.
OPERATORS Allen Glynn 11-12-74

TIME	FUEL USED	GAS FLOW	VOLTS	CURRENT	SET KW	GAS PRES	GAS TEMP	ENG TEMP	GAS BOTTLE WGT
	WGT		VOLTS	AMPS	KW	PSI	°F	°F	#
1520	39.0		468	108	84	700	90°F	170	131.66
1525			468	107	84		90	175	
1530			468	107	84		90	175	
1535			468	107	84		90	175	
1540	18.25		468	107	84	500	90	175	128.30

REMARKS: POWER FACTOR 1.0, FREQUENCY 60 HZ.
TEST TIME 1200 SECONDS

F2-28

HSF-175.1A 1/66

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION
WINDSOR LOCKS, CONNECTICUT 06096

SPACE & LIFE SYSTEMS LABORATORY

LOG OF TEST

TYPE OF TEST: GAS FUMIGATION - GAS #3
TEST ENGINEER: A. RYAN
NAME OF RIG: STANDBY DIESEL - WASTE TR
PROJECT & ENG. ORDER NO.

SHEET 1 OF 1 DATE 11-18-74
TEST PLAN NO.
MODEL NO. 590
PART NO.
SERIAL NO.
OPERATORS

F2-29

TIME	TIME UNITS SEC.	FUEL USED #		GAS FLOW %		VOLTAGE VOLTS		CURRENT AMPS		POWER SET KW		GAS PRESS PSIA		GAS TEMP °F		EXH TEMP °F		GAS BOTTLE			
																		NO.		2722	
1159	0	0		31.5		471		108		84		14.8		95		182					
																		INITIAL	WGT	129.00	
1203	282	4		31.5		471		108		84		14.8		84		185					
																		FINAL	WGT	126.89	
1208	569	8		31.5		471		108		84		14.8		83		185					
1213	855	12		31.5		471		108		84		14.8		84		185					
1218	1143	16		31.5		471		108		84		14.8		83		185					

REMARKS:

78490

HSF-175.1A 1/66

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION
WINDSOR LOCKS, CONNECTICUT 06096

SPACE & LIFE SYSTEMS LABORATORY

LOG OF TEST

TYPE OF TEST: GAS FUMIGATION GAS #3
TEST ENGINEER: A. RYAN
NAME OF RIG: STANDBY DIESEL WASTE TR.
PROJECT & ENG. ORDER NO.

SHEET 1 OF 1 DATE 11-15-74
TEST PLAN NO.
MODEL NO. 150/8
PART NO.
SERIAL NO.
OPERATORS

TIME	TIME UNITS SEC	FUEL USED #	GAS FLOW %	VOLTAGE VOLTS	CURRENT AMPS	SET POWER KW	GAS PRESS PSIA	GAS TEMP °F	ENG TEMP °F		GAS 1	BOTTLES ~~1~~	2	3	4
										NO.		2918			
1508	0	0	85	471	108	84	15.2	63	175						
										Init	WGT	131.39			
1513	322	4	85	471	108	84	15.2	32	175						
										Final	WGT	125.0			
1518	632	8	85	471	108	84	15.2	30	178						
1523	938	12	85	471	108	84	15.2	32	180						
1529	1239	16	85	471	108	84	15.2	34	180						

REMARKS: POWER FACTOR 1.0 FREQUENCY 60 Hz

78484

HSF-175.1A 1/66

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION
WINDSOR LOCKS, CONNECTICUT 06096

SPACE & LIFE SYSTEMS LABORATORY

LOG OF TEST

TYPE OF TEST: GAS FUMIGATION-CALIBRATION
TEST ENGINEER: A. RYAN
NAME OF RIG: STANDBY DIESEL-WASTE TR.
PROJECT & ENG. ORDER NO.

SHEET 1 OF 1 DATE 11-18-74
TEST PLAN NO.
MODEL NO.
PART NO.
SERIAL NO.
OPERATORS: Allan Ryan

TIME	TIME UNITS SEC	FUEL USED #	GAS FLOW %	VOLTAGE VOLTS	CURRENT AMPS	POWER SET KW	GAS PRESS PSIA	GAS TEMP °F	ENG. TEMP °F
1245	0	0		471	108	84			180
1250	282	4		471	108	84			182
1255	567	8		471	108	84			182
1300	849	12		471	108	84			183
1305	1125	16		471	108	84			184

REMARKS: POWER FACTOR 1.0, FREQUENCY 60HZ.

78492

F2-31

HSF-175.1A 1/66

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION
WINDSOR LOCKS, CONNECTICUT 06096

SPACE & LIFE SYSTEMS LABORATORY

LOG OF TEST

TYPE OF TEST: GAS FUMIGATION - CAL
TEST ENGINEER: A. RYAN
NAME OF RIG: STAND-BY DIESEL - WASTE TP
PROJECT & ENG. ORDER NO.:

SHEET 1 OF 1 DATE 11-15-74
TEST PLAN NO. 84KW
MODEL NO.
PART NO. GAS BOTTLE NO
SERIAL NO.
OPERATORS A. RYAN / E. YOUNG

TIME	TIME UNITS	FUEL USED		GAS FLOW	~~VOLTAGE~~	VOLTAGE		CURRENT		PWR SETTING		GAS PRES		GAS TEMP		ENG TEMP	GAS BOTTLE
	SEC	LBS		%	~~VOLTS~~	VOLTS AC		AMPS		KW		PSIA		°F		°F	INITIAL WT = N/A
0857	0	0		N/A		469		107		84		N/A		N/A		175	FINAL WT = N/A
0901	282	4				470		107		84						175	
0906	573	8				470		108		84						175	
0911	880	12				470		108		84						175	
0916	1167	16				470		108		84						175	
0921	1447	20				470		108		84						175	

GAS FREED

REMARKS:

78481

F2-32

HSF-[illegible]A 1/66

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION
WINDSOR LOCKS, CONNECTICUT 06096

SPACE & LIFE SYSTEMS LABORATORY
LOG OF TEST

TYPE OF TEST: GAS FUMIGATION - CAL.
TEST ENGINEER: A. RYAN
NAME OF RIG: STANDBY DIESEL-WASTE TREATMENT
PROJECT & ENG. ORDER NO.

SHEET 1 OF 1 DATE 11-13-74
TEST PLAN NO.
MODEL NO.
PART NO.
SERIAL NO.
OPERATORS [signature] 11/13/74

TIME	TIME UNITS SEC.	FUEL USED #	GAS FLOW	VOLTAGE VOLTS	CURRENT AMPS	SET POWER KW	GAS PRESS PSI	GAS TEMP °F	ENG TEMP °F	GAS BOTTLES # 1	2	3	4
1345	0	0	—	470	108	84	—	—	180				
1350	287	4	—	470	108	84	—	—	180				
1355	584	8	—	468	107	84	—	—	180				
1400	877	12	—	470	108	84	—	—	180				
1405	1167	16	—	470	108	84	—	—	180				

REMARKS: POWER FACTOR 1.0, FREQUENCY ~~60 HZ~~ al. 59 1/4 HZ START 59 1/2 STOP.

78480

F2-33

K-114

FORM WATW

1A-2652

SCIENTIFIC GAS PRODUCTS, INC.

CERTIFICATION

ALL VALUES MOLE PERCENT UNLESS NOTED

GAS	REQUESTED	ACTUAL
AIR		
AR		
CO_2	3.5%	[illegible]
CO	30.1%	[illegible]
HE		
H_2	16.4%	16.4%
CH_4	1.1%	1.12%
N_2	Balance	
O_2		
Ethylene	0.6%	0.60%

THC AS CH_4 ____ PPM DEWPOINT ____

PRESSURE [illegible] PSI ANALYST [illegible]

REPLACEMENT MIXTURE CAN BE REORDERED BY REQUESTING STOCK No. ____ FROM YOUR NEAREST SCIENTIFIC GAS PRODUCTS, INC. SALES OFFICE.

EDISON, NEW JERSEY

HOUSTON, TEXAS — MELROSE, MASS.

F2-34

FORM WATW

1A-4365

SCIENTIFIC GAS PRODUCTS, INC.

CERTIFICATION

ALL VALUES MOLE PERCENT UNLESS NOTED

GAS	REQUESTED	ACTUAL
AIR		
AR		
CO_2	3.5%	[illegible]
CO CP	30.1%	[illegible]
HE		
H_2	16.4%	[illegible]
CH_4	1.1%	1.09%
N_2	Bal	Bal
O_2		
C_2H_4	.06%	0.61%

THC AS CH_4 ____ PPM DEWPOINT ____

PRESSURE [illegible] PSI ANALYST [illegible]

REPLACEMENT MIXTURE CAN BE REORDERED BY REQUESTING STOCK No. [illegible] FROM YOUR NEAREST SCIENTIFIC GAS PRODUCTS, INC. SALES OFFICE.

EDISON, NEW JERSEY

HOUSTON, TEXAS — MELROSE, MASS.

K-114

FORM WATW

1A-2414

SCIENTIFIC GAS PRODUCTS, INC.

CERTIFICATION

ALL VALUES MOLE PERCENT UNLESS NOTED

GAS	REQUESTED	ACTUAL
AIR		
AR		
CO_2	3.5%	[illegible]
CO CP	30.1%	[illegible]
HE		
H_2	16.4%	[illegible]
CH_4	1.1%	[illegible]
N_2	Balance	
O_2		
Ethylene	0.6%	[illegible]

THC AS CH_4 ____ PPM DEWPOINT ____

PRESSURE [illegible] PSI ANALYST [illegible]

REPLACEMENT MIXTURE CAN BE REORDERED BY REQUESTING STOCK No. ____ FROM YOUR NEAREST SCIENTIFIC GAS PRODUCTS, INC. SALES OFFICE.

EDISON, NEW JERSEY

HOUSTON, TEXAS — MELROSE, MASS.

FORM WATW

1C-2245

SCIENTIFIC GAS PRODUCTS, INC.

CERTIFICATION

ALL VALUES MOLE PERCENT UNLESS NOTED

GAS	REQUESTED	ACTUAL
AIR		
AR		
CO_2	19.9%	[illegible]
CO CP	19.1%	[illegible]
HE		
H_2	[illegible]	[illegible]
CH_4	[illegible]	[illegible]
N_2		
O_2		
C_2H_4	[illegible]	[illegible]

THC AS CH_4 ____ PPM DEWPOINT ____

PRESSURE [illegible] PSI ANALYST [illegible]

REPLACEMENT MIXTURE CAN BE REORDERED BY REQUESTING STOCK No. [illegible] FROM YOUR NEAREST SCIENTIFIC GAS PRODUCTS, INC. SALES OFFICE.

EDISON, NEW JERSEY

HOUSTON, TEXAS — MELROSE, MASS.

K-114

FORM WATW

#1 end

1C-3328

SCIENTIFIC GAS PRODUCTS, INC.

CERTIFICATION

ALL VALUES MOLE PERCENT UNLESS NOTED

GAS	REQUESTED	ACTUAL
AIR		
AR		
CO_2	19.9%	20.0%
CO CP	19.1%	[illegible]
HE		
H_2	Bal	Bal
CH_4	16.1%	16.1%
N_2		
O_2		
Ethylene	[illegible]	[illegible]

THC AS CH_4 ____ PPM DEWPOINT ____

PRESSURE [illegible] PSI ANALYST [illegible]

REPLACEMENT MIXTURE CAN BE REORDERED BY REQUESTING STOCK No. [illegible] FROM YOUR NEAREST SCIENTIFIC GAS PRODUCTS, INC. SALES OFFICE.

EDISON, NEW JERSEY

HOUSTON, TEXAS — MELROSE, MASS.

K-114

FORM WATW

1C-2274

SCIENTIFIC GAS PRODUCTS, INC.

CERTIFICATION

ALL VALUES MOLE PERCENT UNLESS NOTED

GAS	REQUESTED	ACTUAL
AIR		
AR		
CO_2	3.5%	3.51%
CO CP	30.1%	30.2%
HE		
H_2	16.4%	16.2%
CH_4	1.1%	1.02%
N_2	Balance	Balance
O_2		
Ethylene	0.6%	0.602%

THC AS CH_4 ____ PPM DEWPOINT ____

PRESSURE [illegible] PSI ANALYST [illegible]

REPLACEMENT MIXTURE CAN BE REORDERED BY REQUESTING STOCK No. ____ FROM YOUR NEAREST SCIENTIFIC GAS PRODUCTS, INC. SALES OFFICE.

EDISON, NEW JERSEY

HOUSTON, TEXAS — MELROSE, MASS.

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K 114

FORM WATW #2.02

11-3.163

SCIENTIFIC GAS PRODUCTS, INC.

CERTIFICATION

ALL VALUES MOLE PERCENT UNLESS NOTED

GAS	REQUESTED	ACTUAL
AIR		
AR		
CO_2	19.9%	20.3%
CO c.P.	19.1%	19.3%
HE		
H_2	Bal.	Bal.
CH_4	16.2%	16.5%
N_2		
O_2		
ETHYLENE	9.1%	9.16%

THC AS CH_4 ____ PPM DEWPOINT ____

PRESSURE 1500 PSI ANALYST E.D.

REPLACEMENT MIXTURE CAN BE REORDERED BY REQUESTING STOCK NO. 10632 FROM YOUR NEAREST SCIENTIFIC GAS PRODUCTS, INC. SALES OFFICE.

EDISON, NEW JERSEY

HOUSTON, TEXAS — MELROSE, MASS.

F2-35

FORM WATW

11-2772

SCIENTIFIC GAS PRODUCTS, INC.

CERTIFICATION

ALL VALUES MOLE PERCENT UNLESS NOTED

GAS	REQUESTED	ACTUAL
AIR		
AR		
CO_2	47%	47.0%
CO		
HE		
H_2		
CH_4	Bal.	Bal.
N_2		
O_2		

THC AS CH_4 ____ PPM DEWPOINT ____

PRESSURE 1000 PSI ANALYST E.D.

REPLACEMENT MIXTURE CAN BE REORDERED BY REQUESTING STOCK NO. 10587 FROM YOUR NEAREST SCIENTIFIC GAS PRODUCTS, INC. SALES OFFICE.

EDISON, NEW JERSEY

HOUSTON, TEXAS — MELROSE, MASS.

K-114

FORM WATW

11-2918

SCIENTIFIC GAS PRODUCTS, INC.

CERTIFICATION

ALL VALUES MOLE PERCENT UNLESS NOTED

GAS	REQUESTED	ACTUAL
AIR		
AR		
CO_2	47%	47.0%
CO		
HE		
H_2		
CH_4	Bal.	Bal.
N_2		
O_2		

THC AS CH_4 ____ PPM DEWPOINT ____

PRESSURE 1000 PSI ANALYST E.D.

REPLACEMENT MIXTURE CAN BE REORDERED BY REQUESTING STOCK NO. 10682 FROM YOUR NEAREST SCIENTIFIC GAS PRODUCTS, INC. SALES OFFICE.

EDISON, NEW JERSEY

HOUSTON, TEXAS — MELROSE, MASS.

FJ-35

K-114

FORM WATW

1C-2630

SCIENTIFIC GAS PRODUCTS, INC.

CERTIFICATION

ALL VALUES MOLE PERCENT UNLESS NOTED

GAS	REQUESTED	ACTUAL
AIR		
AR		
CO2	3.5%	3.46%
CO CP	30.%	29.5%
HE		
H2	16.?%	17.1%
CH4	1.1%	1.01%
N2	Balance	
O2		
Ethylene	0.6%	0.614%

THC AS CH4 ____ PPM DEWPOINT ____

PRESSURE 1500 PSI ANALYST [illegible]

REPLACEMENT MIXTURE CAN BE REORDERED BY REQUESTING STOCK No. ____ FROM YOUR NEAREST SCIENTIFIC GAS PRODUCTS, INC. SALES OFFICE.

EDISON, NEW JERSEY

HOUSTON, TEXAS — MELROSE, MASS.

F2-36

K-114

FORM WATW

C-1807

SCIENTIFIC GAS PRODUCTS, INC.

CERTIFICATION

ALL VALUES MOLE PERCENT UNLESS NOTED

GAS	REQUESTED	ACTUAL
AIR		
AR		
CO2	3.5%	3.45%
CO CP	30.1%	30.1%
HE		
H2	16.4%	16.4%
CH4	1.1%	1.12%
N2	Balance	
O2		
Ethylene	0.6%	0.60%

THC AS CH4 ____ PPM DEWPOINT ____

PRESSURE 1500 PSI ANALYST JWC

REPLACEMENT MIXTURE CAN BE REORDERED BY REQUESTING STOCK No. ____ FROM YOUR NEAREST SCIENTIFIC GAS PRODUCTS, INC. SALES OFFICE.

EDISON, NEW JERSEY

HOUSTON, TEXAS — MELROSE, MASS.

K-114

FORM WATW

1C-1302

SCIENTIFIC GAS PRODUCTS, INC.

CERTIFICATION

ALL VALUES MOLE PERCENT UNLESS NOTED

GAS	REQUESTED	ACTUAL
AIR		
AR		
CO2	3.5%	3.50%
CO CP	30.1%	30.1%
HE		
H2	16.4%	16.4%
CH4	1.1%	1.07%
N2	Balance	
O2		
Ethylene	0.6%	0.60%

THC AS CH4 ____ PPM DEWPOINT ____

PRESSURE 1500 PSI ANALYST JWC

REPLACEMENT MIXTURE CAN BE REORDERED BY REQUESTING STOCK No. ____ FROM YOUR NEAREST SCIENTIFIC GAS PRODUCTS, INC. SALES OFFICE.

EDISON, NEW JERSEY

HOUSTON, TEXAS — MELROSE, MASS.

K-114

FORM WATW

1C 1221

SCIENTIFIC GAS PRODUCTS, INC.

CERTIFICATION

ALL VALUES MOLE PERCENT UNLESS NOTED

GAS	REQUESTED	ACTUAL
AIR		
AR		
CO2	3.5%	3.45%
CO CP	30.1%	30.1%
HE		
H2	16.4%	16.4%
CH4	1.1%	1.05%
N2	Balance	
O2		
Ethylene	0.6%	0.60%

THC AS CH4 ____ PPM DEWPOINT ____

PRESSURE 1500 PSI ANALYST JWC

REPLACEMENT MIXTURE CAN BE REORDERED BY REQUESTING STOCK No. ____ FROM YOUR NEAREST SCIENTIFIC GAS PRODUCTS, INC. SALES OFFICE.

EDISON, NEW JERSEY

HOUSTON, TEXAS — MELROSE, MASS.

ORIGINAL PAGE IS OF POOR QUALITY

K-114

(4)

FORM WATW

1C-1814

SCIENTIFIC GAS PRODUCTS, INC.

CERTIFICATION

ALL VALUES MOLE PERCENT UNLESS NOTED

GAS	REQUESTED	ACTUAL
AIR		
AR		
CO2	3.5%	3.45%
CO CP	30.1%	30.0%
HE		
H2	16.4%	16.4%
CH4	1.1%	1.12%
N2	Balance	
O2		
Ethylene	0.6%	0.59%

THC AS CH4 ____ PPM DEWPOINT ____

PRESSURE 1500 PSI ANALYST [illegible]

REPLACEMENT MIXTURE CAN BE REORDERED BY REQUESTING STOCK No. ____ FROM YOUR NEAREST SCIENTIFIC GAS PRODUCTS, INC. SALES OFFICE.

EDISON, NEW JERSEY

HOUSTON, TEXAS — MELROSE, MASS.

K-114

(7)

FORM WATW

1C-2031

SCIENTIFIC GAS PRODUCTS, INC.

CERTIFICATION

ALL VALUES MOLE PERCENT UNLESS NOTED

GAS	REQUESTED	ACTUAL
AIR		
AR		
CO2	3.5%	3.4%
CO	30.1%	30.1%
HE		
H2	16.4%	16.2%
CH4	1.1%	1.05%
N2	Balance	
O2		
Ethylene	0.6%	0.60%

THC AS CH4 ____ PPM DEWPOINT ____

PRESSURE ____ PSI ANALYST [illegible]

REPLACEMENT MIXTURE CAN BE REORDERED BY REQUESTING STOCK No. ____ FROM YOUR NEAREST SCIENTIFIC GAS PRODUCTS, INC. SALES OFFICE.

EDISON, NEW JERSEY

HOUSTON, TEXAS — MELROSE, MASS.

APPENDIX F3

PYROLYSIS SYSTEM FLEXIBILITY

F3

PYROLYSIS SYSTEM FLEXIBILITY

IUS SIZE VARIATIONS

The adaptability of the URDC and Barber-Colman systems to various sized IUS installations is not greatly different. The upper size limit for both is considerably greater than would be required by any anticipated IUS. Factors affecting the larger end of the size spectrum are discussed in more detail in Appendix H4.

The minimum practical size for a fixed bed gasifier feeding unshredded refuse is approximately the size chosen for this study. Down to this size range, the URDC system does not require shredding and, therefore, has the advantage of a significantly simpler front end system than the Barber-Colman system. Some further reduction in capacity could be obtained by simply lowering the design bed loading and keeping the same gasifier size. Below that, the URDC system would require at least coarse shredding and, therefore, would have relatively little advantage over the Barber-Colman system from a front end system standpoint.

IUS FUEL VARIATIONS

The previous sections have discussed the various potential uses for a fuel gas in an IUS assuming that the main fuel was conventional. In most cases there is no fundamental difference between the behavior of a pyrolysis gas in a mixed pyrolysis gas/oil fuel or pyrolysis gas/natural gas system.

If the primary fuel itself becomes dual fuel, some complications arise. However, no basic problem would be anticipated for an engine application. The pryolysis gas would be mixed with the natural gas when on natural gas and substituted for natural gas when on oil. Hardware and control requirements would be increased somewhat since three fuels would have to be accommodated. The most significant limit probably is that the basic dual fuel engine would have to have the capability of modulating the gas/ oil balance during normal operation.

Fuel cells probably do not lend themselves to a dual fuel approach since the reforming step would require considerably different operating conditions and catalysts. Gas turbines again would be a problem with a dual fuel system. Most gas turbines are designed to burn either gas or oil. Although there is no fundamental reason why dual fuel capability could not be achieved, there are some significant practical limitations. In general, oil and gas firing require significantly different burner configurations. This is especially important for a gas turbine since the requirements for temperature control and flatness of exit temperature profile are quite severe. Most gas turbine burners **must also** operate within a tight space envelope, and there simply is not enough room for separate oil and gas burners. The best candidate gas turbines for a dual fuel application, therefore, would be those where the burner was separate from the

main engine envelope. If a gas turbine had dual fuel capability, the addition of pyrolysis gas firing capability would not be a significant problem.

If the primary IUS fuel were a relatively dirty fuel such as coal or residual oil, rather than natural gas or a clean distillate oil, a different set of problems and constraints arise. Without preprocessing (i.e., gasification), coal could only be fired in a boiler. At the IUS size, the efficiency of power generation using this approach is very poor. If the coal were gasified, the product could be utilized in diesels, gas turbines or fuel cells. However, the only type of commercial coal gasifier likely to be available in the reasonably near future in the appropriate size range is the traditional gas producer. The fuel would have to be limited to a non-caking coal if the conventional producer were used. This system would provide a primary fuel quite similar to the air gasifier product. Therefore, it could be mixed with the URDC system gas. The Barber-Colman gas could certainly be used in combination with the producer gas, but it is a significantly different fuel so the advantage of interchangeability would be lost.

One further step that could be taken for a system consisting of producer gas primary fuel and air gasifier pyrolysis system would be to combine the gas cleanup systems downstream of the basic gasifiers. That is, mix the raw producer gas and the raw

URDC product and then do the scrubbing together. This approach would not appear to be feasible with the Barber-Colman system.

Primary gasification and pyrolysis system could be integrated even further for the URDC approach. For example, the producer and the waste gasifier are quite similar pieces of process equipment and, therefore, a combination of coal and waste gasification in a single gasifier would appear to be feasible. The major problems in fixed bed gasification are associated with material flows into and within the gasifier. The best approach, therefore, would appear to be to gasify the coal in the waste gasification system rather than the other way around.

The major problem in coal gasification is the tendency of all, except non-caking, coals to form large clinkers in the bed. This obviously must be avoided. It is our belief that mixing of coal and refuse before introduction into the gasifier would prevent this if there were sufficient volume of waste in proportion to the coal. Since the energy density of coal is approximately ten times the energy density of the solid wastes, there is a reasonable chance that a coal/waste mix in the proportions expected for an IUS application could be handled by an ordinary air gasifier designed for solid wastes.

Further difficulty with coal fed producers is that fines do not make a suitable feedstock. Again, some fines probably could be

introduced together with the waste feed without excessive loss or other problems. In addition, there is a good possibility that coal fines could be introduced into the bottom of the gasifier by being blown in with the gasification air (or more likely a combination of air and steam). This would be particularly appropriate if the gasification air heater were eliminated or at least reduced in output temperature with the additional heat requirement at the bottom then coming from direct partial combustion of coal.

The combination of coal and waste gasification would have extremely important advantages, especially from a capital cost standpoint. Operating problems and costs also would be minimized because of the much simpler system resulting from the combination. In general, the major difficulty with coal primary fuel would be the very high capital cost associated with its use, particularly in the small sizes needed for an IUS application. The combination approach would make a real contribution to bringing these costs down towards acceptable levels. Again, this advantage **would only be** possible with the URDC approach and not with the Barber-Colman system.

Residual oil can be used directly in more varieties of equipment than coal. It is significantly cheaper to burn in boilers than coal. It can be burned directly with only minor pretreatment in some diesels and gas turbines. However, the only suitable

diesels are the very large units, mostly of European manufacture, that would not fit most IUS applications. Similarly, the only gas turbines suitable are the large heavy duty industrial machines. Most of the gas turbine experience with residual fuels has been with European gas turbines. Again, these would be too large for typical IUS application.

Therefore, a major pretreatment step would be required just as is the case for coal. The only commercially available processes would be gasifiers such as the Texaco process. These usually produce something resembling a producer gas so that the same general comments apply as for coal gasification.

Residual oil also probably could be gasified in either Barber-Colman or the URDC systems. However, the proportions that would be possible are open to question. There is no obvious reason that we are aware of that would limit the Barber-Colman system, so that 100% residual oil feed might well be possible. The fixed bed gasifier could accept oil with either the refuse feed or by introduction with the gasification air. A quite significant fraction of the feed (on an energy basis) could be oil, but 100% certainly would not be possible.

TYPES OF ENERGY NEEDED

There are many potential uses for the fuel gases that could be produced from a waste pyrolysis system. The major relevant ones have been discussed in some detail in Section 1 of this Appendix.

All discussions were based on the premise that pyrolysis (Barber-Colman or URDC) is not suitable for the production of pipeline or synethetic natural gas (SNG). That is, even the medium Btu pyrolysis gases would require considerable added processing before they would be suitable for pipeline applications. Methanation would be required, and this is a costly step in dollars as well as in energy. Furthermore, it is not a well developed process, and the major development efforts are directed towards the very large SNG facilities which would be orders of magnitude larger than a waste processing plant. In addition to increasing the fuel gas heating value to the thousand Btu per cubic foot HHV level, the **process would also** have to stabilize the composition to a relatively high degree.

As a result of these considerations, it was felt that the complexity, cost, energy loss and added technical risk involved in upgrading any pyrolysis gas to SNG would be excessive.

A further restriction is that it was assumed that the pyrolysis gas would not be distributed for residential uses such as stoves, driers, individual water heaters, etc. This type of distribution is quite feasible although it would require a higher level of compositional stability than the large scale uses discussed. The major problems would be the high CO content of any of the pyrolysis gases and the need to make custom modifications to a relatively large number of low cost appliances. The modification:

would be necessary for any pyrolysis gas, since standard residential appliances are available only for natural or liquified petroleum (LP) gas.

The major application for the fuel gas then is firing in a prime mover such as a diesel, fuel cell or gas turbine. The second category of potential uses is firing for direct heat, as for example in boilers. Both fuel gases can supply all of these needs, and there is no across the board difference between them. Their performance in diesels will be about the same; in fuel cells the URDC system will have a small advantage; in gas turbines the performance should be essentially the same; in boilers the medium Btu Barber-Colman gas will have a very slight efficiency advantage over the URDC product. In most cases, hardware modifications will be required to adapt either fuel. In some cases, these will be simpler for the Barber-Colman product since the relative values of fuel and air flow for it are closer to conventional fuels. Therefore, the changes in relative orifice areas, etc. would be smaller. However, the low Btu variation of the fuel cell system is simpler than the Barber-Colman version since no reforming is required for the URDC product. The availability of off-the-shelf gas turbine hardware for low Btu gas firing, but not medium Btu gas firing, is likely to become quite good because of the effort being expended in coal gasification.

WASTE TYPE VARIATIONS

The difference in performance between the Barber-Colman and URDC systems can be expected to remain fairly constant as the waste type varies. As the waste feed becomes better from an energy standpoint, both systems put out more useful energy; as the feed gets poorer, both put out less energy.

The major influence on system energy is the water content of the waste feed. The major cause of water variation is whether or not sludge is to be processed along with the solid wastes. The average water content of approximately 50% used for the mixed refuse/sludge in this study seems to be quite representative of this type of service and would be roughly the upper bound for expected water content. Somewhat higher allowable water contents could be processed for both the Barber-Colman system and the URDC system with scrubbed fuel gas. The limiting points are when the Barber-Colman pyrolysis system efficiency goes to zero and when the nitrogen dilution of the URDC product gas gets too high resulting in a fuel gas that requires supplementary fuel to maintain ignition. Both systems probably reach their respective limits at approximately the same input water levels. With a close coupled URDC system, the high water vapor levels in the unscrubbed fuel gas would cause fuel gas combustion stability problems at a lower input water content than for the scrubbed system.

The inert content of the solid waste can vary over a very considerable range. The addition of sludge tends to lower average inert content, as would any source separation of bottles or cans. Conversely, source separation of paper would tend to increase the inert percentage. Residential solid wastes often have very high inert contents. For example, the fraction inerts measured during the URDC 140 lb/hr pilot plant program ranged from 18 to 46% by weight (Table 1, Appendix A-1). The waste feed all was residential refuse, taken as it was put out on the street for collection. Quantities of refuse collected for a run represent a sample size range of 300 to 2,000 pounds. In all cases, the refuse was processed without any problems assignable to high or low inert contents. The inert content could drop considerably lower than the minimum that would be expected in an IUS application without any problem being anticipated in slag removal.

The sensitivity of the Barber-Colman system to high or low inert contents is unknown. However, there is no obvious reason to expect problems at either end of the scale.

Higher sulfur, chloride or flouride content, such as might be expected from high plastic wastes, should not have a serious effect on the performance of the furnace or the gasifier itself. However, their undesirable products would have to be removed by the fuel gas scrubbers. The one potential problem that has been identified is the possibility of undesirable reactions between

the gas phase constituent and the lead bath in the Barber-Colman system.

WASTE QUANTITY AND IUS LOAD VARIATIONS

The quantity of waste collected in a basically residential situation can be quite variable, both from day to day and from season to season. Furthermore, it would be useful to be able to control the processing rate on a diurnal basis to match the electrical demand. This would keep the swings in pyrolysis gas/primary fuel ratio within acceptable bounds. Thus, a practical pyrolysis system should be controllable over a fairly wide range of load swings.

The URDC system has been operated over a wide range of loads (see Table 1, Appendix A-1) without encountering any operating problems due to excessively high or low output rates. The fixed bed process upper limit is much higher than the design upper limit for the URDC system. This is demonstrated by Torrax operation at bed loading several times the URDC bed loadings. In practice, the upper limit is set by the maximum acceptable particulate carry-out and by the capacity of the system to supply gasification air and remove fuel gas at the required flows and pressures.

The lower limit for the URDC system is set by the need to maintain slagging conditions. The relative heat loss increases as the output goes down, and a point is reached where slagging

temperatures cannot be maintained without supplementary energy. (This point was not reached in the URDC tests described in Appendix A-1.)

As a result of these considerations, it can be seen that the URDC system has a great deal of flexibility with respect to processing rates and the actual capacity for a given system to a large extent will be a design choice. The design range of processing rates generally used for this system has been from 50% of the design point to 20% above the design point.

The upper limit for the Barber-Colman system would be the point at which insufficient heat can be transferred to the waste in the furnace to complete pyrolysis. Thus, if in a particular furnace design, with a particular waste feed and bed thickness, the required residence time were 10 minutes, that would be the upper limit. Any increase in through put, obtained by either increasing bed thickness or reducing residence time, would result in incomplete pyrolysis of some of the waste unless the radiant tube surface temperature were increased. Increases in tube temperature probably would be of relatively little help, since the heat transfer limit should be within the bed itself rather than from tube surface to bed surface.

As the through put was lowered, either the residence time would increase or the bed thickness decrease, thus, making the heat

transfer easier and allowing a reduction in tube surface temperature. If the radiant tube burner was carefully matched at the high end of its output range, it would be capable of operating to quite low through puts without problems. A four to one turndown ratio would be reasonable.

In summary, both systems appear to have adequate capacity for handling at a level of through put variations that would be expected in an IUS. The Barber-Colman system at the design point is very close to the upper limit of the basic process but has very considerable flexibility for reduction of through put. On the other hand, the URDC system, at its design point, is closer to the middle of the potential process range. As a result, it has less downward flexibility but more upward flexibility.

TWENTY-FOUR HOUR VERSUS EIGHT HOUR PROCESSING

Both processes are much more readily adaptable to 24 hour operation than eight hour operation. However, both systems also are capable of operating on an eight hour schedule, though at the cost of increased capital, maintenance and lowered efficiency. The difference between the two systems probably is not great.

For the relatively short down periods that would be encountered in eight hour operation, the system probably would be kept warm (i.e., furnace temperatures maintained near their normal operating temperature) to minimize maintenance requirements and also

to minimize operating manpower during the daily start ups and shutdowns.

At the design IUS size, the Barber-Colman system is smaller than the URDC system and has a lower heat loss. However, the radiant tube burners could be expected to have a minimum output of roughly 1/4 their maximum output which is too high for a holding mode. Thus, provision may have to be made for on-off firing during holding operation, in addition to the modulated firing that would be required for normal operation. The Barber-Colman furnace has a relatively low efficiency so that a relatively large quantity of energy would be required in proportion to the energy actually lost from the furnace.

Some other practical difficulties are encountered with the Barber-Colman system. Conventional radiant tube burners are designed for gas firing (natural or LP). Thus, the fuel required for start up and hot holding would have to be gaseous or an entirely new set of radiant tube heating hardware would have to be developed. If natural gas was not available, then LP gas would have to be used. This tends to be an expensive fuel, and availability problems might also be encountered. Furthermore, the burner only could be set up for a particular gas which would have to be the pyrolysis gas. Thus, a separate system would be required to premix the supplementary fuel with enough air to simulate the pyrolysis gas. This should not cause any unusual

problems for the pyrolysis gas/natural gas combination. For example, the ratio of fuel heating values is quite similar to the ratio for natural gas/propane, which is a common combination for industrial furnace fuels when natural gas is supplied under an interruptable contract. However, the simulation of pyrolysis gas with propane is a considerable jump and might cause problems.

The somewhat higher heat loss of the URDC system, assuming intermittent firing of the Barber-Colman radiant tubes, is balanced by the higher inherent efficiency of the process. Furthermore, a significant proportion of the total energy required to keep the system warm - and possibly the entire amount - could come from the waste rather than from the primary fuel. However, not enough work has been done in this area to establish the requirements with any degree of certainty.

APPENDIX F4

FIRE, SAFETY, AND POLLUTION CONSIDERATIONS FOR PYROLYSIS PROCESSES

F4

FIRE, SAFETY, AND POLLUTION CONSIDERATIONS FOR PYROLYSIS PROCESSES

FIRE PROTECTION

Refuse handling, treatment and disposal systems all have inherent fire protection problems exhibited through a long history of costly incidents. Both of the pyrolysis concepts will have to deal with these problems and provide protection through systems engineering and management. The major considerations can be divided into the following three categories: (1) refuse handling, (2) the manufacture of flammable gases, and (3) the use of these flammable gases.

The following are preliminary guidelines and considerations for providing the required protection. The objectives are safety to the person in the area and the protection of the system equipment in order to prevent long and costly repairs and downtimes following a fire incident. The guidelines are discussed for refuse handling and flammable gas manufacture. The same guidelines are then suggested for the user subsystem review as applicable. This user review should be conducted with a slightly different viewpoint, i.e., what should be added in this subsystem to protect it from malfunctions in the pyrolysis system?

Refuse Handling and Preprocessing

1. Fire incidents will occur rather frequently and should be included in the system design.

2. Unless specific design guidelines are followed, these fires will be difficult to extinguish.
3. The structures and components of the system will be subject to damage by any fire not easily controlled and extinguished within a few (probably 4 or 5) minutes.
4. Ignition sources in the refuse handling equipment will be found throughout the refuse collection and preprocessing equipment; anyplace where there is a build up of refuse.
    - Collection Carts
    - Loaders
    - Conveyers
    - Shredders
    - Silos
    - Hoppers
5. The design should attempt to minimize the quantity of refuse at any of these areas. Where this is impractical, an attempt to isolate several small quantities from each other in order to limit the amount subject to any one fire and to limit the amount of equipment exposed to any one fire.
6. Means should be provided for rapid and positive detection of fire and/or flammable gases in these areas and the actuation of at least a local alarm and possibly the notification of a central station or the local fire department.
7. Built-in extinguishing equipment should be provided for rapid application of water before the structure and equipment

7. (Continued)

are subject to high temperatures. This may require automatic actuation by the detection equipment.

8. Provisions should make for quick, easy, and safe access to the fire section for manually completing the extinguishment. Depending on the configuration of a particular section and the equipment exposed to it, some may require rapid dumping of the refuse.

9. Provisions should be made for rapid cleanup following a fire incident and a procedure for returning the entire system to service.

10. Systems engineering and planning will be required to safe guard the pyrolysis reactor during a fire incident in the refuse handling or preprocessing equipment. The reactor cannot be cooled down rapidly; it is subject to severe damage by exposure to water from extinguishing equipment either inside or outside when applied to a localized area. The reactor heat and the flammable product gases will be a continuing potential source of ignition to the refuse approaching it in the loader. The refuse adjacent to the reactor may require dumping prior to the application of any extinguishing agent. The reactor should be switched over to a hot standby mode in order to quickly return it to service after the incident. Isolation on the intake side will be required to prevent leakage of product gases into the refuse.

11. The product gas delivery to the user subsystem should be interrupted and switched to a flaring mode immediately and automatically upon detection of a fire in order to preclude the possibility of propogating the fire or its ill effects to downstream equipment.

Pyrolysis Gas Manufacture and Processing

12. The reactor should be operated at a positive pressure such that any leakage that occurs will be of product gases to the relatively unenclosed volumes surrounding it. Positive steps must be taken to prevent the uncontrolled leakage of air or any other oxidizing agent into the closed product gas volume.
13. Large pressure relief valves should be provided at several places in the reactor, and the product gas cleaning system to automatically vent sudden pressure excursions and explosive pressure buildup. Provisions will be required to prevent the blocking of the pressure relief valve by refuse being lifted by the movement of the gases during venting action.
14. Emergency isolation valves should be installed in the hot gas outlet duct between the reactor and the gas cleaning equipment and at the system outlet to isolate flame fronts in the section where they originate.
15. An automatic fire and explosion detection and alarm system should be installed to perform the following functions:

15. (Continued)

A. Detection and Alarm Initiation

Alarm initiation provisions should be provided for manual actuation by the operators and by automatic detection equipment including:

- Fire detectors (heat, smoke, optical) in and around the refuse collection, handling and loading section, in the top section of the reactor, in the gas cleaning section and in the system outlet.
- Pressure detectors actuated by static pressure level and by rate of use in all sections of the system.
- Oxygen level buildup in the reactor and product gas cleaning system and ducting.
- Flammable gas buildup in surrounding closed or partially closed volumes.
- Water flow of the extinguishing system.
- Carbon monoxide levels in surrounding areas.

B. Alarm Signals

The alarm signals should, as a minimum, sound a local alerting device such as a horn or bell. If the system is to be unattended at any time, the alarm system should transmit a signal to a central station or to the local fire department.

C. Functions

The actuation of the alarm system should automatically:

15. C. (Continued)

- Close all isolation valves.
- Switch the system to a standby mode.
- Stop the supply of gas to the user.
- Ventilate areas where flammable or toxic gases may build up to dangerous levels.

The User of Pyrolysis Gases

16. Review the foregoing guidelines and incorporate as appropriate at the IUS user subsystem location.

Fire Safety Comparison of the Barber-Colman and URDC Systems

The differences in fire safety factors between the URDC and Barber-Colman pyrolysis concepts are few but important. First, the Barber-Colman concept requires shredding of refuse, while the URDC system does not have this requirement. Experience shows that shredding devices are particularly susceptible to fires and explosions. This is an inherent risk in shredding caused by the sudden application of mechanical energy to the various and mixed fuels of refuse.

A second important difference between the two concepts is the temperature distributions within the pyrolysis reactors. In the URDC reactor, the pyrolysis gases are collected at the top of the reactor at a temperature well below ignition temperature. In the Barber-Colman reactor, the gases are maintained at high

temperature throughout and exposed to the hot radiant tubes. The result is that oxygen entering the reactor with the refuse or by any other means will be more likely to cause violent pressure spikes in the Barber-Colman reactor than in the URDC reactor. This is further complicated by the potential for corrosion and leakage of the radiant tubes directly exposing the reactor atmosphere to a combustion reaction. In the URDC reactor, oxygen introduced with the refuse will have an opportunity to diffuse to a uniform safe level without being exposed to high temperatures. Oxygen entering the lower section of the URDC reactor is completely reacted on a controlled basis.

Flammability Limits

It should be noted that many combustion properties in common use, such as flammability limits and ignition temperature, are really not fundamental properties. Their values tend to be quite sensitive to apparatus and test conditions. Though they may be quite useful, they should be used with a great deal of caution.

The two properties of most relevance to the pyrolysis program would be the lower explosive limit (LEL) and maximum safe O_2 content. LEL is useful as a very rough measure of limits imposed on fuel utilization equipment in the broad range of applications where the fuel and air are premixed. For example, spark ignition gas engines, dual fuel or fumigation applications in

diesels and "fumigated" gas turbines. Here, LEL can be used as a very rough guide to relative performance limits. Since the performance limits can have a direct bearing on capital costs and operating costs (efficiency), this is an area of prime importance to the program.

The use of maximum safe O_2 content to describe the rich limit is a convenient way to deal with air leakage hazard question. O_2 concentration can be measured, while the upper explosive limit (UEL) cannot. Maximum O_2 covers the whole rich side of the fuel/air/diluent system, while UEL represents only a single point. O_2 concentration can be related to the leakage air as follows:

$$\%O_2 = \frac{0.21\ V_a/V_g + O_{2fg}}{V_a/V_g + 1} \times 100$$

Where V_a and V_g are the volume flows of leakage air and fuel gas, and O_{2fg} is the O_2 already in the fuel gas. Similarly, maximum allowable leakage can be related to the maximum allowable O_2 content ($O_{2\ max}$) as follows:

$$(V_a/V_g)\ max = \frac{1 - O_{2fg}/O_{2max}}{0.21/O_{2max} - 1}$$

Assuming a conservative 5% O_2 limit and taking the fuel gas oxygen content is 1.4% (fixed bed gasifier) the limit becomes:

$$(V_a/V_g)_{max} = 0.225$$

It should be noted when evaluating hazards, that it is not possible to place a specific value on LEL, UEL or maximum O_2 for the product from a particular gasifier. This is because the gasifier product composition will vary significantly both during steady state running (variations in operating conditions or feed composition) and especially during transients. Therefore, any numbers given should be treated as rough approximations of what might be expected during steady operation. This is especially true when dealing with start up and shutdown processes where the fuel starts out and ends up as essentially an inert gas and gets to the steady state condition by a continuous and unpredictable change in composition and resultant properties.

Potential hazards can be dealt with by monitoring O_2 content where fuel is kept and air might leak in, and monitoring LEL in areas where there is air and fuel might leak in. Since the fixed bed system is analogous to a gas producer, and the Barber-Colman system is analogous to a furnace with a combustible atmosphere, there is no reason to believe that hazard questions cannot be dealt with by conventional means when the program reaches that stage.

At this stage, the best way to estimate limits is to compare the pyrolysis gas to similar manufactured gases. Since the fixed bed gas is quite similar to producer gas, producer gas limits can be used directly. The Barber-Colman gas falls between the

various manufactured gas for which data is conveniently available Therefore, its limits, and particularly the UEL, are somewhat less certain.

Recommended values for the fixed bed air gasifier product are:

LEL = 20%

UEL = 80%

Recommended values for the Barber-Colman product are:

LEL = 4-6%

UEL = 40-50%

Data on maximum safe oxygen content for various gases is given in Table 1. The information in the Table was taken from Combustion, Flames and Explosions of Gases, Lewis and vonElbe, Academic Press, New York, 1961.

Some indication of the effect of ambient temperature on limits is given by Figure 1. The effect of pressure on the lean limit is quite small, but can be very significant on the rich side.

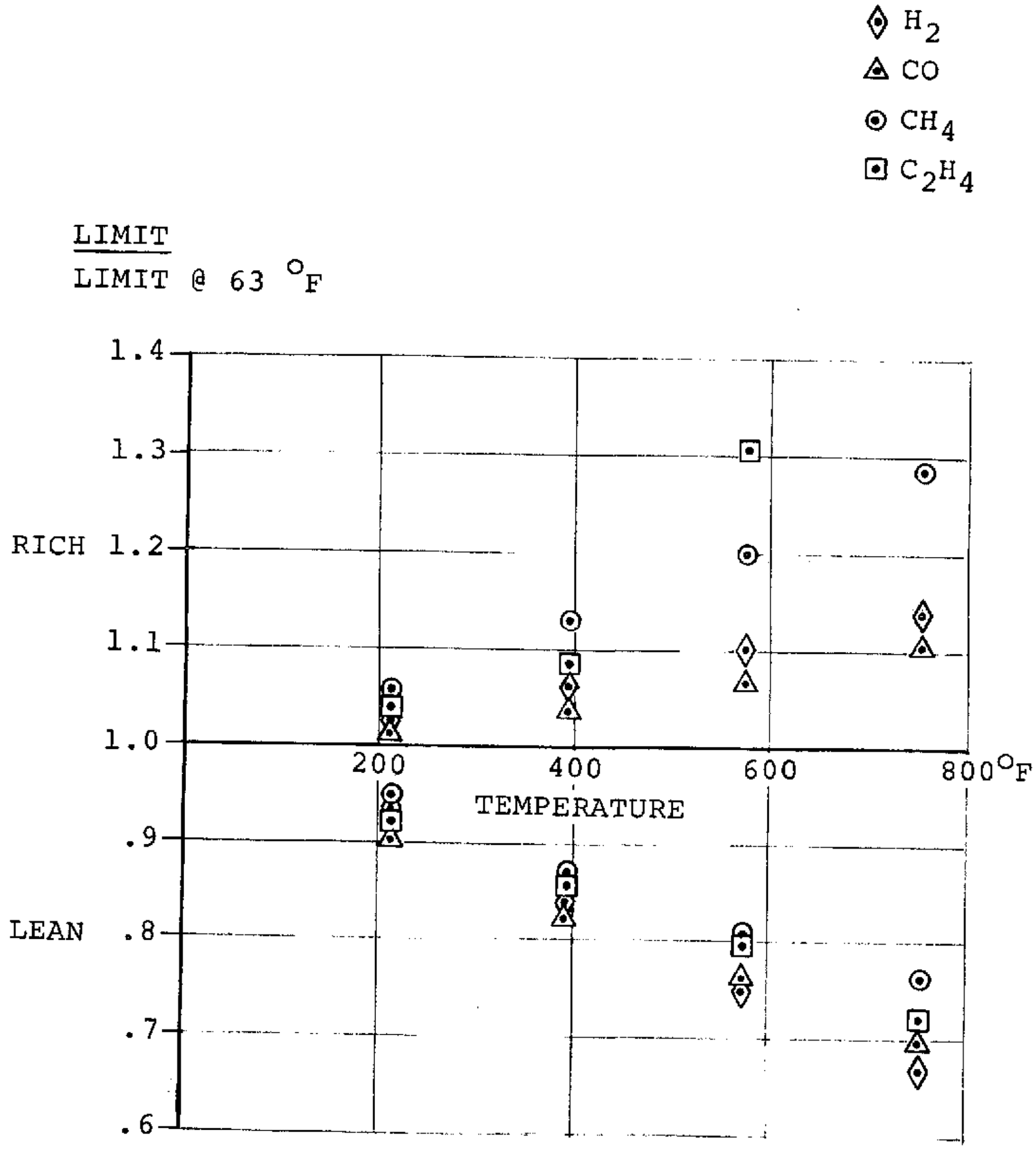
AIR POLLUTION

Any scrubbed fuel gas should be a clean fuel from an air pollution control standpoint. If raw fuel gas is burned, there is some possibility of excessive emissions of sulfur oxides, chlorides, and possibly fluorides. Also possible with unscrubbed gas is increased nitrogen oxide formation due to the ammonia formed

TABLE 1

Maximum Safe Percentage of Oxygen in Mixtures of Combustibles with Air and CO_2 or N_2 (Room Temperature and One Atmosphere Pressure)

	Maximum Safe Percentage of Oxygen	
Combustible	CO_2 as Diluent	N_2 as Diluent
Hydrogen	5.9	5.0
Carbon Monoxide	5.9	5.6
Methane	14.6	12.1
Ethane	13.4	11.0
Propane	14.3	11.4
Butane and Higher Hydrocarbons	14.5	12.1
Ethylene	11.7	10.0
Propylene	14.1	11.5
Cyclopropane	13.9	11.7
Butadiene	13.9	10.4
Benzene	13.9	11.2



DATA FROM "COMBUSTION OF GAS" GAS ENGINEERS HAND BOOK, NY. 1965

EFFECTS OF TEMPERATURE ON FLAMMABILITY LIMITS

from the nitrogen in the original wastes. For example, there is evidence that under some circumstances fuel nitrogen, which includes ammonia, tends to form much larger quantities of nitrogen oxides than the same amount of pure nitrogen (cf Ref. 1, 2).

Limited experimental evidence (3) indicates that inorganic particulate emissions from the unscrubbed fixed bed gasifier product would just meet federal incinerator particulate emission codes without further scrubbing. Particulate emission levels with the Barber-Colman system are as yet unknown. Experimental evidence (3) indicates that high CO content in a fuel gas does not produce significantly higher CO emissions than natural gas. This is not unexpected since CO tends to be an important intermediate product in CH_4 oxidation (cf Ref. 4, 5).

Nitrogen oxide emissions with the scrubbed Barber-Colman gas should be comparable to conventional fuels. Nitrogen oxide emissions for scrubbed air gasifier products should be significantly lower. Since nitrogen oxide formation is a non-equilibrium process, it is strongly influenced by flame temperature which will be some lower for the low Btu gas.

WATER POLLUTION

Neither the Barber-Colman or URDC pyrolysis system should cause significant water pollution problems. For the particular IUS assumed for this study, the waste water treatment system should

be able to handle the pyrolysis system waste water without any particular difficulties. Basically, the added loading to the existing treatment system due to the addition of pyrolysis is quite small.

Actual experience on the treatability of the effluent water from a pyrolysis gas scrubbing system is very limited. Union Carbide has indicated that the scrubber effluent from their oxygen gasifier is treatable by their biological process with no problems. Since they use the same basic combination of precipitator and wet scrubber as proposed for the URDC system, their results can be taken as a good indication of the treatability of the URDC system effluent. This is particularly true considering the high level of dilution with other wastes that would be encountered in the IUS.

The Barber-Colman system does have an advantage in that the char produced can be used as the first stage cleanup step for the scrubber water. (It should be noted that a first stage cleanup is required for the Barber-Colman system in order to bring its discharge to the normal levels produced by the fixed bed system, since the bulk of the condensed organics for the URDC system are removed in the electrostatic precipitator and never reach the waste water.)

There is some evidence that the pyrolysis char would be useful for waste water treatment. However, the characteristics of an

activated carbon are very dependent on the activation step. The feedstocks for the production of commercial activated carbon are first carbonized and then activated in a completely separate step. Successful activation requires careful control of temperature and atmosphere and is quite specific to the kind of adsorption service that the carbon is destined for. The production of a char in a single step in the pyrolysis furnace, without separate activation, is not likely to lead to a particularly effective activated carbon. Comparing the organic loading to be removed from the scrubber effluent (0.025 lb) to the char available (0.049 lb) it would appear that the likelihood of achieving anything approaching adsorption at these loading levels without having a relatively high grade of activated carbon is rather low. The most likely function of the char in the waste water contacting system, therefore probably would be more as a gross filter rather than as an adsorbent.

One possible pollution problem associated with the char/waste water treatment is the production of H_2S by biological activity. This is favored by the high organic loadings, the presence of sulfates, and the low concentration of dissolved oxygen in the scrubber effluent.

RESIDUE DISPOSAL

The least residue disposal problems are encountered with a slagging system such as URDC's. Due to the material's high

density and stability, it could be disposed of as a clean stable fill in many situations. If not, the density is high enough so that the disposal volume required at a landfill would be negligible in comparison to raw refuse. Since there is no possibility for organic contamination of the material and since the material is oxidized, the potential for any pollution problems such as leachate contamination of ground water are very small.

The Barber-Colman system residue also is a relatively clean material, although its density and stability will be poorer than that of slag. The major potential for land pollution hazards would appear to be improper process operations. Residence time in the Barber-Colman system is very low, and there is nothing in the process configuration that automatically insures proper operation or complete treatment of a residue (as there is in a slagging system). Even aside from the possibility of grossly improper system operation, the low residence time in the furnace means that the heat transfer characteristics of the refuse bed must be carefully controlled or incomplete processing must result. For example, any local pile up of extra refuse due to improper feeder operation could be expected to lead to locally imperfect processing; excessive balling of refuse in the shredder, or excessively thick material getting through the shredder, also would mean that the material would not be fully pyrolized in the time available.

These factors are particularly critical when it is considered that the effective bed thickness must be limited to something at most a few inches thick if anyting approaching the postulated residence time is to be achieved.

Most of any unpyrolized residue probably would be separated with the char and recycled through the furnace. However, the characteristics of the residue and how it is to be disposed of would tend to be set by the fact that some inadequately processed material will show up in the residue to be disposed of. The best way to characterize the residue from the Barber-Colman system would be to consider it equivalent to the residue from a conventional incinerator. If the incinerator is well designed and properly operated, the residue will be very clean and innocuous. If not, the residue can be just as bad from a potential land pollution standpoint as raw refuse.

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APPENDIX G

DEVELOPMENT STATUS OF THE URDC AND BARBER-COLMAN PYROLYSIS SYSTEMS

DEVELOPMENT STATUS OF THE URDC AND BARBER-COLMAN PYROLYSIS SYSTEMS

INTRODUCTION

Neither the URDC nor the Barber-Colman system can be considered as fully developed processes. However, the two are at very decidedly different stages of development. The URDC system appears to be much closer to operational hardware and has a much lower level of risk associated with it. The Barber-Colman system appears to require considerable further testing and development before it will be ready for an IUS demonstration.

REACTOR DEVELOPMENT STATUS

URDC

Fixed bed gasification has a considerable history, since it is related to the traditional gas producer. These gasifiers were in common use many years ago for the production of industrial fuel gases from coal. Variations designed for refuse processing under slagging conditions (Torrax, URDC, Union Carbide) have been built and operated in both large and small sizes. The kind of operation for the waste processing versions has ranged from pilot plant to something approaching production. However, full production operation has not been achieved; fuel gas production (as opposed to refuse disposal) has not been attempted for an air gasifier refuse disposal system; no attempt has been made to design or develop a unit for production operation at the size

level associated with an IUS. Neither does detailed data sufficiently precise for sizing of the gasifier or ancillary equipment exist.

Thus, it is safe to conclude that basic process feasibility has been demonstrated and that there are no fundamental obstacles to the development of a successful fixed bed gasifier for the desired service. However, development problems certainly can be expected, particularly for a relatively, sophisticated application such as the IUS. In addition to optimum sizing of the reactor and ancillary equipment, many development problems will be associated particularly with the ancillary equipment (e.g., feeders, fuel gas scrubber, etc.) and will be discussed in a later section.

Problem areas that can be anticipated for the basic gasification process itself include:

1. The optimization of gasifier geometry to minimize channeling and maximize process rate and efficiency.
2. The design of the slag flow/tap region to insure trouble free automatic slag tapping.
3. The design of an optimum gasifier wall structure for the hot zone to minimize heat loss and maximize life.

Even though one or more demonstrated solutions exist for each of these potential problem areas, the achievement of the best solution for a particular application will require some design risks, and the usual level of development problems can be anticipated.

Barber-Colman

The Barber-Colman process has only been tested on a very small scale. Since Hamilton Standard has received very little information on the test results, we are not in a position to make a detailed evaluation of the status of the development program. However, we do have sufficient information to comment on the following areas.

Data Gap - There appear to be large gaps in the measured data. As a result, it is not possible to make a closed mass or energy balance for the Barber-Colman system, under any operating condition, without making important fundamental assumptions that cannot be related directly to the process actually occurring by either theoretical or experimental means.

The uncertainty that this lack introduces is quite large. This can be illustrated by examining the Bureau of Mines pyrolysis data(1) for simple batch pyrolysis in an 18 inch diameter retort. Comparing the LHV of the pyrolysis gas produced to the LHV of the input solid wastes, the following range of values were obtained for the total pyrolysis gas LHV:

- For the same retort temperature but different refuse composition: 42-87% of input LHV.
- For the same composition but different retort temperatures: 42-91% of input LHV.

This represents a variation of over 2:1 in the total energy of the gas produced for relatively small variations in process conditions.

Therefore, we can only conclude that the Barber-Colman system is likely to be subject to large and unpredictable variations in its gas production performance particularly as system scale is changed.

Completeness of Pyrolysis - Another major aspect of the Barber-Colman system which is likely to lead to significant development problems is the degree of completeness of pyrolysis. This is an area of performance prediction that is somewhat easier to deal with on a rational basis than detailed output characterization. The process heat requirements are substantial, and high transfer rates are difficult to obtain. As a result, the heat transfer process can be expected to be controlling.

Heat transfer rates tend to be low for several reasons. These reasons include the following:

- Refuse has a multi-layered structure, and the bulk of its constituents have relatively low thermal conductivities. Therefore, it tends to be a good insulator.
- The evolution of water and pyrolysis products from the waste tends to insulate it and protect it from convective heat transfer and to a certain extent from radiative heat transfer.

To achieve substantially complete pyrolysis of the feed requires that it remain in the furnace for sufficient time to insure that all of it receives enough heat to complete the pyrolysis process. If conditions within the furnace change in such a way as to lower heat transfer rates, the residence time must be increased to make up the difference. For a given residence time, the most important parameters would seem to be the bed thickness and physical structure. The physical characteristics of the bed will be determined largely by the shredding and feeding processes. Significant changes in bed thickness or other physical characteristics have the potential of causing very large increases in required residence time. This is particularly true, since the design residence time is very low for a process of this sort. As a result, there is a high level of risk involved in predicting the capacity of a scaled system. This risk only can be reduced by a fairly extensive experimental program designed to develop an understanding of the heat transfer process as it actually occurs within the Barber-Colman system. The only alternative is to build the system at a particular scale and then experimentally determine what its capacity is. Since performance is dependent not only on the furnace itself but also the shredding and feeding systems, any fundamental changes that must be made after a system is built are likely to be very expensive.

As a result of these considerations, the only way to scale up with a reasonable degree of conservatism would be by maintaining

the residence time, bed thickness, and fineness of shredding substantially the same as for the pilot plant.

One important implication of heat transfer control is that experimentation on any material that does not have the same heat transfer properties as municipal solid wastes (geometry, thermal conductivity, etc.), no matter how similar to municipal solid wastes in chemical nature, will not provide all of the answers relevant to solid waste processing.

Another problem area that may be encountered after scaling to a larger size is that even after shredding the material being processed is more likely to be far more heterogeneous with respect to material geometry than for the pilot operation. Unless shredding is done to an extremely fine level, noticeable quantities of thicker material are likely to be found. When this happens, heat transfer within the solid itself is likely to be too slow to allow complete pyrolysis. Balling of metals can produce the same kind of effect.

A final difficulty that should be considered is that the furnace depends on radiative heat transfer but is at the very low end of the temperature scale for successful use of this mode of heat transfer. To quote Trinks[2] from his section entitled "Continuous Furnaces for Temperatures Below 1400F": "As explained in Chapter 3, the extremely low intensity of radiation at temperatures below 1400F causes difficulty in maintaining uniform

temperatures throughout the furnace. This fact has led to the adoption of forced convection in a majority of furnaces under discussion, as well as furnaces of the batch type." Later in the same section he states: "Continuous furnaces for temperatures below 1200F are always equipped with fans for recirculation."

A simple calculation can be used to illustrate these points. Consider the Barber-Colman 1500 lb/hr furnace design with two 6" diameter radiant tubes approximately 12" long. The energy balance calculation (Appendix C3) indicates a heat requirement of about 1250 Btu/lb which is equivalent to 1.9×10^6 Btu/hr for this capacity. If we assume the radiant tube surface runs at 1400°F, surface temperature of the refuse bed is 800°F, and the emissivity factor is 0.8, the effective heat transfer coefficient is about 22 Btu/hr - ft^2 - °F. The resulting heat transfer at this condition would be about 0.5×10^6 Btu/hr which is a little more than 1/4 of the heat required. Thus, if this furnace is to achieve its design through put, tube surface temperature must increase significantly (lowering the bed surface temperature has little effect on the heat flux). Increasing the surface temperature lowers the furnace efficiency and may push a particular radiant tube combination of material, thickness and construction out of its serviceable range.

Three examples from the literature can be used to illustrate the difficulties that can be expected as material thickness increases:

1. A 2.5" diameter dry, high density cellulose cylinder (higher thermal diffusivity than wood) was heated at a high rate. After five minutes, the surface reached over 610°F, but the internal temperature at the 1.5" diameter level was still about 210°F. In ten minutes, the surface had reached 840°F, but the inner 1" diameter portion did not reach 500°F until 28 minutes had passed, and substantially complete pyrolysis took over 40 minutes.[3]
2. A review[4] describes a fire protection test on a thick fir lumber panel which had one face exposed to a furnace fire (ASTM E - 119 conditions). In ten minutes, a thermocouple 1/16" from the hot face reached 800°F. Thermocouples 1" from the hot face barely started to rise at ten minutes, reached 200°F in 20 minutes and reached 800°F in something over 40 minutes. Another test described was a burn through test in which one surface of a 1" wood board was exposed to an open gas flame, and the time to burn through to the unexposed side was measured. This time ranged from 23 to 43 minutes.
3. A 0.79" diameter wood dowel was heated in an 880°F oven. The time required for pyrolysis was about 19 minutes.[5]

<u>Char Consumption</u> - The performance calculations have been predicated on the assumption that char can be recycled to extinction in one pass through the furnace, even if air is excluded

from the system. This appears to be a highly questionable assumption. If char oxidation were likely to occur under Barber-Colman furnace conditions, it would seem that the char production without recycling should be lower than it is. The Bureau of Mines' tests which gave about the same gas composition as the Barber-Colman system also had about the same char production, even though the residence time there was several orders of magnitude larger (this assumes that the char data given for the Barber-Colman system is a directly measured value).

A more critical argument can be based on the kinetics of char oxidation by steam. This can be illustrated by the process used to regenerate activated carbon used in waste water treatment. Regeneration usually is done in a multiple hearth furnace. Slowly rotating rabble arms agitate the carbon and rake it to the center and OD on alternate hearths. When it reaches the center or OD, it drops to the next lowest hearth. Heat is provided by gas burners, which also provide controlled amounts of unburned oxygen. Steam is added so that a controlled $CO_2/O_2/$ steam atmosphere can be maintained. The furnace loading is quite low (less than 2 lb/hr-ft^2), and the carbon layer is thin (less than 1/2"). The residence time typically is a total of 30 minutes, distributed as follows: 15 minutes to dry; 5 minutes to pyrolyze adsorbed organics; 10 minutes to oxidize the char remaining in the pore structure after the adsorbed organics are

pyrolyzed. The furnace gas temperatures in the oxidation zone are maintained at approximately 1700°F, and the carbon itself reaches 1500-1650°F. These conditions appear to be much more severe than those encountered in the Barber-Colman furnace. Yet, the only oxidation that occurs is of the char from organics deposited in the pore structure, plus typically 5 to 10% of the carbon itself.(6)

<u>Lead Loss</u> - If we assume that either all relevant phase equilibria will be favorable to lead conservation, or if not, lead conservation will be salvaged by favorable kinetics - and these assumptions appear to be subject to serious question - the problem of lead loss by mechanical means still remains. It would seem that the variety of waste shapes likely to be encountered, such as balled cans, in a production solid waste processing situation is very considerable, particularly if shredding is to a coarser scale than for the Barber-Colman pilot facility. The bed apparently is rather thoroughly agitated and, in fact, must be if adequate heat transfer rates are to be maintained. Thus, it would seem most likely that lead would be caught in the folds of some of the higher melting point metal wastes and trapped there and then carried out of the furnace. Relatively little of this sort of occurrence would be required to produce a significant lead loss in a production situation.

Mechanical Problems - Some of the Barber-Colman furnace internal hardware proposed appears to be more suitable for pilot operation than for production refuse processing operations. For example, the chain arrangement designed to knock residue into the quench tank appears to be in this category. The processing of solid waste tends to be a very severe test of hardware and trouble free operation requires rugged, well thought out and developed equipment.

This is not to say that problems of this type are insurmountable. We simply would point out that the level of development of the Barber-Colman system appears to be still at the stage where subsystems that could be made to work on the pilot scale are borrowed for full scale designs even though they are not really suitable for this entirely different type of service.

ANCILLARY EQUIPMENT DEVELOPMENT STATUS

URDC

Refuse materials handling problems pose severe difficulties for all solid waste processing systems. Perfect solutions have not been found, and design compromises that allow reasonably trouble free operation are the best that can be expected. Any new design for solid waste materials handling hardware can be expected to require a significant development effort before it becomes operational in a production situation. Therefore, the URDC refuse receiving/feeding system is designed on the basis of the

technology or hardware in regular use in the industry. The most serious potential problem is in the feeder itself, and this is designed around developed stationary compactor equipment. Development problems still can be anticipated in this area, but they should not be severe.

Development problems can be expected for other equipment as well. For example, fuel gas scrubbing, slag quench and removal, and miscellaneous fuel gas plumbing subsystems also are areas that can be expected to require some development. However, these do not appear to be particularly different than the problems that can be expected for the Barber-Colman system.

Barber-Colman

The Barber-Colman front end up to the air lock feeder can utilize existing refuse handling technology. Refuse shredding and storage are known troublesome areas. However, a significant amount of development is ongoing in these areas, and installations are presently in operation. The air lock/feeder appears to present a formidable development problem. Simple air lock feeding of either shredded or unshredded refuse is difficult, but the Barber-Colman system places much more stringent requirements on the feeder. For example, the need to distribute the waste in a very thin layer of controlled thickness and density across the width of the lead bath/grate can be expected to require a very significant development effort. This probably will require

several fundamentally different designs and several cycles of testing and redesign.

The remaining equipment development problems can be expected to be in the same magnitude of difficulty as those that would be encountered for the URDC system. Therefore, the major difference between them, as far as ancillary equipment is concerned, is in the much more severe functional requirements for the Barber-Colman feeder.

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APPENDIX H

APPLICATIONS OF THE BARBER-COLMAN AND URDC PYROLYSIS SYSTEMS OTHER THAN FOR AN IUS

APPLICATIONS OF THE BARBER-COLMAN AND URDC PYROLYSIS SYSTEMS OTHER THAN FOR AN IUS

REFUSE DISPOSAL

A general refuse disposal utility should be considered a practical application for a pyrolysis system. Since neither energy recovery nor resource recovery is included, the basic objectives are minimum cost and environmentally acceptable disposal.

For this service, a greatly simplifed version of the fixed bed gasification system would be used. Fuel gas scrubbing would not be required, and the raw gas would be burned in a simple conventional burner designed for raw gas. The gasification air heat would come from direct combustion of recycled raw fuel gas. The result would be an extremely simple, low cost system.

The Barber-Colman system could only be simplified to a very limited extent. Presumably, it would be possible to burn the raw fuel gas and eliminate the scrubber. However, a major difficulty would be encountered in the radiant tube burners. Since these burners have to achieve a very carefully controlled rate of heat release throughout the length of the radiant tubes, we would doubt whether they could be modified to burn warm raw gas. There is no evidence that Hamilton Standard is aware of as to whether or not the inorganic particulate carry-out would be

low enough to allow the system to meet particulate emission codes without fuel gas scrubbing. However, due to inherent low gas velocities from the bed, it would be presumed that particulate pollution would not be a problem. As a result of the first consideration, it would be assumed that either the fuel gas scrubbing step could not be eliminated or the Barber-Colman system would require a considerable quantity of an alternate fuel to provide system heat. Similarly, the char/residue separation step could not be eliminated because the char would be required for first stage scrubber effluent cleanup.

A comparison of the Barber-Colman and URDC systems for this type of service leads to a clear choice in favor of the URDC system. The basic reasons can be summarized as follows:

- Lower Capital Cost
- Lower Operating Cost
- Less Landfill Requirement
- Less Likelihood of Landfill Environmental Problems

Lower capital and operating costs must result even though the basic furnace costs are in the same magnitude since the Barber-Colman system is far more complex than the simplified URDC system. The Barber-Colman system requires shredding, refuse handling for both unshredded and shredded refuse, fuel gas scrubbing or alternate fuel, and char/residue separation while the URDC system requires none of these.

Assuming the residue in both cases would be landfilled, the volume would be considerably lower for the URDC product. The slag produced by the URDC system is a stable, completely inorganic product and, therefore, should present a minimum of potential pollution problems. The Barber-Colman product, if pyrolysis is complete, also should have relatively little pollution potential. However, there is no guarantee that the Barber-Colman system always would be properly operated and, therefore, there is some potential for the production of less than desirable residue.

In summary, the simplified fixed bed gasification system should make a very low cost disposal system, while the Barber-Colman system would not. The Barber-Colman system appears to have no significant advantage over conventional incineration for this application - even if its development were fully and successfully completed and it met the more optimistic projections made for its potential.

ENERGY RECOVERY

If the refuse disposal utility application, discussed in the previous section, is broadened to include energy recovery, the considerations change somewhat, but the same basic results are obtained. The three major candidate uses for energy would be steam raising or gas turbine firing in the near term future and fuel cell systems in the more distant future.

If the product were to be steam, the URDC system would be close coupled with the boiler to simplify the system, reduce capital cost, and improve efficiency. The resulting system would be similar to the one described in the previous section, except the raw fuel gas would be burned in a boiler rather than a flare burner. The efficiency improvement, using the IUS heat balance, would be from about 78% to about 88%.

The Barber-Colman system could probably not be close coupled for reasons discussed in the previous section. However, the exhaust gas from the radiant tubes would be used for steam generation. Assuming the efficiency of the radiant tube plus steam generator combination would be 80% (typical for boilers), the added heat recovery would improve the Barber-Colman system efficiency from 32% under IUS conditions to about 51%. The added dilution by nitrogen in the air gasifier product would increase the boiler flue gas loss slightly, but the effect would be insignificant compared to the efficiency difference between the Barber-Colman and the URDC system. For example, the boiler flue gas loss would increase by about 2%.

The constraints applicable to gas turbine based systems are somewhat different and discussed in depth in Appendix F1. In summary, neither gas would incur significant efficiency penalty as long as suitable hardware is available. The availability of that hardware may be somewhat limited especially for the low Btu

fuel gas, at least until systems are developed for coal gasification service. Since the system efficiency would be much greater for the low Btu gas system - even if it were restricted to somewhat less efficient gas turbine hardware - the URDC system again becomes a clear choice over the Barber-Colman system.

If the gas turbine were part of a combined cycle with a fired rather than an unfired system generator, then the low Btu gas would incur some efficiency penalty. However, this efficiency penalty would be smaller than the efficiency difference between a fired and an unfired combined cycle, which is very much smaller than the efficiency difference between the Barber-Colman and URDC pyrolysis systems. Therefore, the combined system efficiency must still be much greater for the fixed bed system.

The use of a pyrolysis gas in a fuel cell system is discussed in some depth in Appendix F1. The conclusion for a utility application, where 100% pyrolysis gas would be fired, was that both Barber-Colman and URDC products would have certain advantages over conventional fuels but also would have potential problems. The major problems were high olefin content for the Barber-Colman product and high dilution levels for the air gasifier product. Both problems appear solvable but probably have some efficiency penalties attached. However, any conceivable fuel cell efficiency penalty will be negligible compared to the more than two to one efficiency penalty that the Barber-Colman

pyrolysis system has relative to the fixed bed gasifier. Therefore, the clear choice between systems again is the URDC fixed bed gasifier.

RESOURCE RECOVERY

If the refuse disposal utility application discussed in the previous two sections was expanded to include maximum resource recovery, the choice between systems is not as clear. Table 1 is a good indication of the possibilities. It does not appear that either system has a clear across the board advantage.

For maximum resource recovery, the fixed bed system would be combined with a conventional front end separation system. Thus, some fiber recovery would be possible. If energy recovery is included, the fixed bed gasifier has a significant advantage in this category, as discussed in the previous section. The Barber-Colman system, on the other hand, would use a back end resource recovery system so that only inorganics could be recovered. However, this is not likely to be a very significant advantage for the fixed bed system.

Char could be recovered only from the Barber-Colman system. Whether this is an advantage or a disadvantage cannot be proven at this stage of development. If the char turns out to be usable as an activated carbon substitute, it would be an advantage. Certainly, there is some evidence that indicates that

TABLE 1
RESOURCE RECOVERY CATEGORIES

	URDC	Barber-Colman
Energy	High	Low
Fiber	Some	None
Metals	Yes	Yes
Char	None	Yes
Slag Products	Yes	None

this is a possibility. However, experience in marketing solid waste pyrolysis chars to date has been completely unsuccessful.

Both systems could recover metals. It is not likely that there will be a very large advantage in either front or back end separation. There is significantly more experience to date with front end separation. The Barber-Colman system does have the potential for recovery of low melting point metals from the lead bath. However, we have seen no evidence that demonstrates the efficiency or even feasibility of this approach. There is a serious possibility that lead losses, due to simple physical carry-out alone, could be significant. In this case, the losses might well out weigh the gains. If the Barber-Colman lead bath system does prove to be a more efficient recovery approach for low melting point metals than front end separation, it would have an advantage.

Slag production is unique to the fixed bed system. Again it is debatable whether this is a significant advantage from a resource recovery viewpoint. Some rather preliminary work has been done on the manufacture of relatively sophisticated and high value construction materials from this material. These products range from cast stone substitutes to abrasion resistant pipe. However, their technical and economic viability has not been demonstrated. On a simpler level, slag can be air cooled to produce an aggregate of good quality. This is not a high value product

but does have some ecological advantages (e.g., minimizing quarrying requirements). It would be more attractive in those parts of the country where natural stone suitable for aggregates does not occur.

The major difference in resource recovery potentially between the two systems probably is energy recovery (which would favor URDC) and the difference between a front end separation system processing raw refuse versus a back end system processing an ash residue. It probably is easier to separate metals from the residue (if only inorganic products are desired) rather than from the shredded refuse. However, neither should be considered easy or even possible without further development of special process equipment. If the key to success is development - and from a practical standpoint it probably is - then front end separation has an advantage. There are a considerable number of full scale front end resource recovery systems either in operation, under construction or have had contracts awarded. On the other hand, there is only one contract that we are aware of for a full back end system (Raytheon using Bureau of Mines technology for resource recovery from incinerator residues), and it is our understanding that construction has not yet started because the incinerator supplying the residue is to be shut down.

SIZE FLEXIBILITY

This is another category in which neither system appears to have a clear advantage. The projected capital costs for the fixed

bed system are somewhat lower than for the Barber-Colman system, and the difference stays relatively constant over the whole likely size range. At the low capacity end of the scale, materials handling becomes the limiting factor. The Barber-Colman system requires shredding, which tends towards operational problems at the low output end unless the shredder is considerably oversized. Oversizing the shredder greatly increases capital cost. The fixed bed system uses what is basically stationary compactor technology. This tends to be less troublesome than shredding, particularly in smaller sizes.

For the fixed bed system, the main upper size limit is set by the desire to shop fabricate the hardware and still have minimum shipping problems. Another limit is that gasifier height probably will get excessive if the capacity gets too large, however, it is not directly proportional to reactor diameter. The capacity at the practical upper limit depends on the design bed loading. For conservative bed loadings and air gasification, the optimum size probably is in the 100 to 300 tons/day range. For oxygen gasifiers, the maximum capacity is considerably larger. For larger systems, multiple modules would be used and would be desirable from a reliability standpoint.

The upper size limit of the Barber-Colman system is difficult to estimate. Certainly, furnaces of the type required can be built in rather large sizes. Since the system is essentially

heat transfer limited, scaling would have to be at a constant bed thickness if the residence time were to be maintained constant. In order to make a reasonably conservative estimate, we have to assume furnace loading at demonstrated levels. The performance numbers given by Barber-Colman indicate their pilot plant is rated at 60 lb/hr and has a lead bath area of approximately 3.5 ft^2. This gives a furnace loading of about 17 lb/hr/ft^2. This would indicate that a 200 ton/day furnace would require a bath area in the magnitude of 1,000 ft^2. The width probably would be limited to something on the order of 10 feet or less before the job of airlock feeding a very thin and carefully controlled layer of refuse became overwhelming. Therefore, the furnace length would be about 100 ft. This length would appear to be approaching a size where constructional and operational problems would start to arise.

COAL GASIFICATION

Coal gasification is a category in which the only choice is the URDC system. As discussed in Appendix F3 fixed bed gasification is an approach that has considerable promise for gasifying coal/solid waste mixtures in which a major portion of the energy comes from coal.

A major fundamental difference between solid wastes and coal is that solid wastes are mainly volatile, while coals are mainly fixed carbon. Thus, pyrolysis is controlling for solid wastes,

while char gasification is controlling for coal. Since the fixed bed system does both in an integrated fashion, it can deal with both feedstocks. This is a demonstrated fact. On the other hand, the Barber-Colman system is basically a pyrolysis furnace. As such, it can only gasify fixed carbon by superimposing some sort of gasification step on the pyrolysis process. Supposedly, this is adequate for the gasification of the char produced from solid wastes even when air is excluded from the system. However, we have seen no convincing experimental or theoretical demonstration of this. Even if it would work as postulated for solid wastes, it seems inconceivable that it would be possible to gasify the very high fixed carbon levels that are obtained from coal. In addition, coal gasification would be carried out for the purpose of maximum energy recovery, and the Barber-Colman system has unacceptably low efficiency for this purpose.

APPENDIX I1

PYROLYSIS DEVELOPMENT PROGRAM PLAN

PYROLYSIS DEVELOPMENT PROGRAM PLAN

The technology of pyrolysis, though ancient, has been only experimentally applied to the disposal of solid waste material during the last decade. As evidenced by the analytical comparison, accomplished in the study reported herein, the time has come to close the loop on pyrolysis development and fabricate and test pyrolysis hardware for practical application to the routine disposal of solid refuse as well as the useful recovery of the energy content of the solid refuse.

This section describes the overall program, of which the study reported herein is a part of the initial step, through which a practical pyrolysis system can be fabricated, tested and integrated in a practical application in which the energy available from the input solid waste can be beneficially recovered. The program presented assumes the availability of an existing design so that it can move directly from the present study into hardware fabrication. Overall program objectives are shown in Table 1. Specifically, this section contains:

- The general approach to the program in terms of tasks and their interrelationships
- A suggested schedule for accomplishing these tasks
- General task descriptions

PYROLYSIS DEVELOPMENT PROGRAM OBJECTIVES

- IDENTIFY ONE OR MORE VIABLE DESIGN CONCEPTS
- FABRICATE ONE OR MORE DEMONSTRATION PYROLYSIS UNITS
- ESTABLISH SATISFACTORY INITIAL PERFORMANCE OF UNIT
- DEMONSTRATE LIFE OF UNIT AND ACCOMPLISH TEST OBJECTIVES
- FABRICATE SUCH GAS CLEANUP EQUIPMENT AS NECESSARY FOR ENERGY USE APPLICATION
- INTEGRATE WITH A "REAL-LIFE" REFUSE DISPOSAL AND ENERGY USE APPLICATION

TABLE 1

PROGRAM APPROACH

A straight forward program is envisioned for the fabrication, delivery, test and integration of a Hamilton Standard design for a slagging, vertical-shaft, partial air oxidation pyrolysis reactor with a nominal capacity of twelve tons per day of typical municipal refuse along with up to eight tons per day of sewage sludge. Such peripheral equipment as may be necessary or desirable to prepare the product gas of the pyrolysis reactor for integration with an appropriate energy consuming device is considered part of the "pyrolysis system" in this discussion. Exact planning for this peripheral equipment must await an indication of the more promising applications.

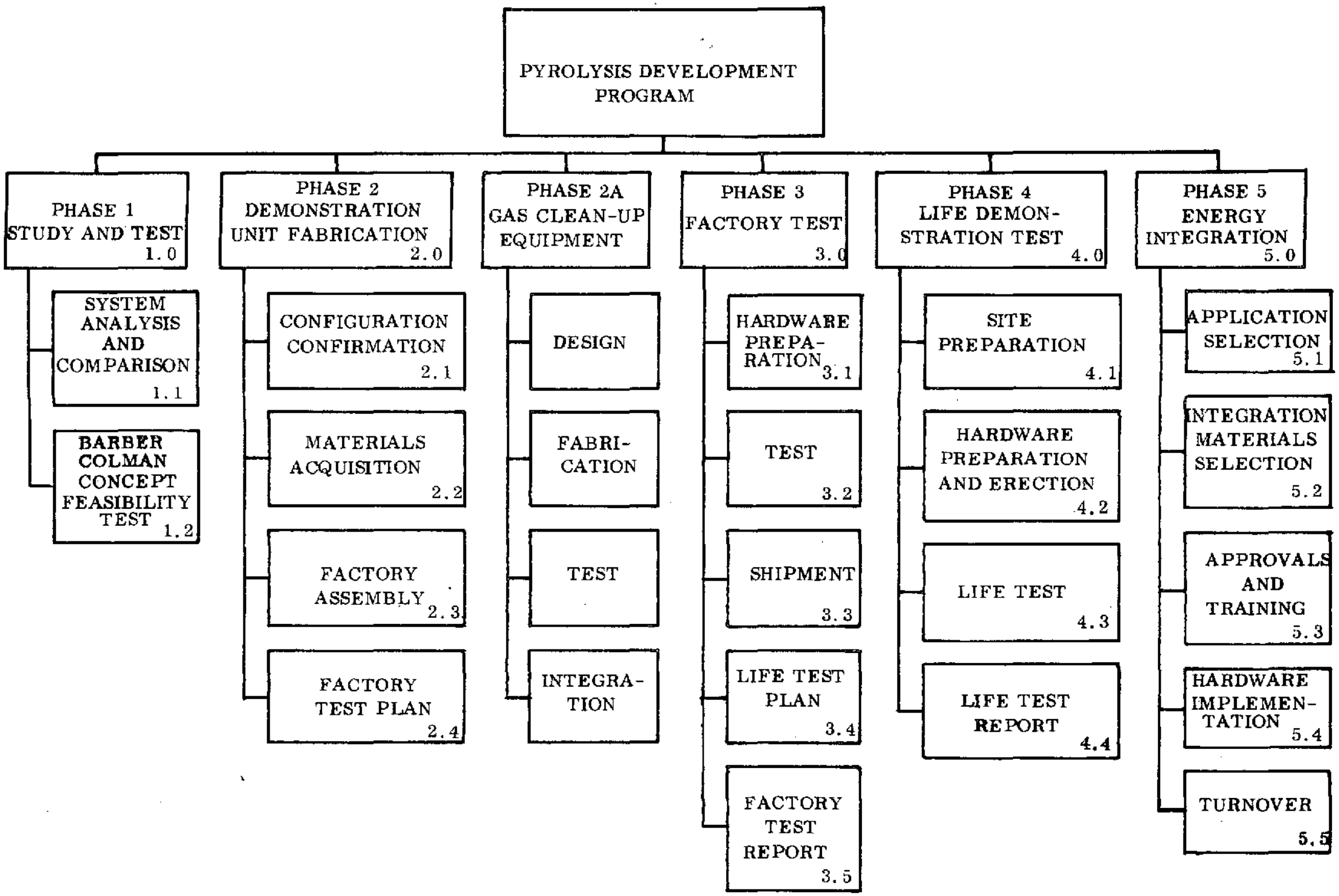
Figure 1 shows the Work Breakdown Structure for the overall Pyrolysis Development Program.

Phase 1

Phase 1 has been completed. The analytical comparison of the URDC design concept and the Barber Colman unit is reported herein. Test of the Barber Colman unit is reported separately.

Phase 2

The critical first steps of Phase 2 will involve confirmation of the configuration of the Hamilton Standard design and the configuration of installation interface requirements for the life test installation. Immediately upon completion of these steps, materials should be placed on order and component part fabrication



PYROLYSIS DEVELOPMENT PROGRAM WORK BREAKDOWN STRUCTURE
FIGURE 1

should commence in order to reduce lead-time on the completed assembly. The unit would then be assembled at the factory for check-out and pre-shipment performance verification testing. In parallel with the fabrication period, the factory test program should be planned in detail and the test plan approved by the NASA.

Phase 2A

While sufficient information concerning end-use is not available to discuss the clean-up requirements of the gas for the ultimate energy application, it is important not to lose sight of the need for planning and implementing hardware in the event the end-use requires gas clean-up. While some applications would require no clean-up hardware (a close-coupled boiler, for instance) it will be desirable to accomplish some clean-up for demonstration purposes and work toward defining this part of the program should commence immediately.

Phase 3

The factory test period is a critical period in preparation for the life test demonstration. During this period, the suitability of the fabricated hardware for undertaking a long term test is determined in an atmosphere in which correction of evident deficiencies is most readily and expeditiously accommodated by the designers and fabricators of the equipment. The discipline of the factory and the urgency of a ship date combine to create the most favorable possible environment for efficiently achieving readiness of the equipment for a successful test.

This phase would also include life test planning as well as actual shipment of the unit to NASA-JSC so that Phase 4 can commence with the hardware in place.

Phase 4

As the factory test nears completion, the housekeeping aspects of site preparation at NASA-JSC should be accomplished with the provision of electrical power to the site, plumbing of water for cooling and fire protection, preparation of trash holding facilities and any other provisions unique to the specific site characteristics. The unit would then be checked out in place and the life test would be conducted in accordance with the plan generated and approved in Phase 3 toward the overall accomplishment of test objectives defined in the interim study report previously submitted and summarized as Table 2. Obviously, this "life test" is an extended period of development testing on the pyrolysis hardware and is intended to provide the confidence in the hardware necessary to a "real world" application. Appendix I2 provides greater detail.

During the period of performance of Phase 4, any gas clean-up equipment required should be fabricated in accordance with the description of Phase 2A and integrated with the pyrolysis test for check-out. Prior to the availability of such clean-up equipment, product-gas should be flared through a burner provided with the basic pyrolysis hardware.

TABLE 2

PYROLYSIS DEVELOPMENT PROGRAM
TEST OBJECTIVES

FACTORY TEST

- Confirm Basic Reactor Operation
- Gross Reactor Performance
  - Capacity
  - Gas Generation
  - Slag Generation
- Confirm Suitability for Extended Testing

LIFE (DEVELOPMENT) TEST

- Energy Recovery
  - Hot Gas Generation Rate and Heating Value
  - Cold Gas Generation Rate and Heating Value (With Ø2A Hardware)
- Gas Composition
  - Gas Constituents
  - Organics, Oil and Gas Carry-over
    * Out of Reactor
    * Out of Ø2A Hardware
  - Particulate Carry-over
    * Out of Reactor
    * Out of Ø2A Hardware

TABLE 2 (Cont'd)

- Cleanliness of Product Gas Combustion
  - * Out of Reactor
  - * Out of Ø2A Hardware
- Design Point Size Evaluation
  - Optimum Rate per Unit Area
  - Feed Rate Variation Capability
- Slag Production Rate
- Refuse Composition Variability
  - Effect on Energy Recovery
  - Effect on Gas Composition
  - Effect on Design Point Size Evaluation
  - Effect on Slag Output
- Start-up/Shutdown Evaluation
  - Routine Operation
  - Variation in Shift Cycle
    - * Continuous
    - * 8-Hour Day
- Operation and Maintenance Evaluation
  - Desired Degree of Control Automation
  - Major Component Life Determination
  - Major Component Maintenance Routine
- Fuel
  - Coal

TABLE 2 (Cont'd)

- Fuel
  - Coal
    * Maximum Addition Practical
    * Modifications to Improve Performance
  - Residual Oil
    * Maximum Addition Practical
    * Modifications to Improve Performance

INTEGRATED TESTS (BOILER GAS UTILIZATION)

- Gas Utilization Efficiency
- Refuse Disposal/Gas Utilization Optimization
  - Continuous Operation
  - 8-Hour Operation
  - Peak Matching
- Operator Manpower Requirements
  - Skills
  - Shift Manning

Phase 5

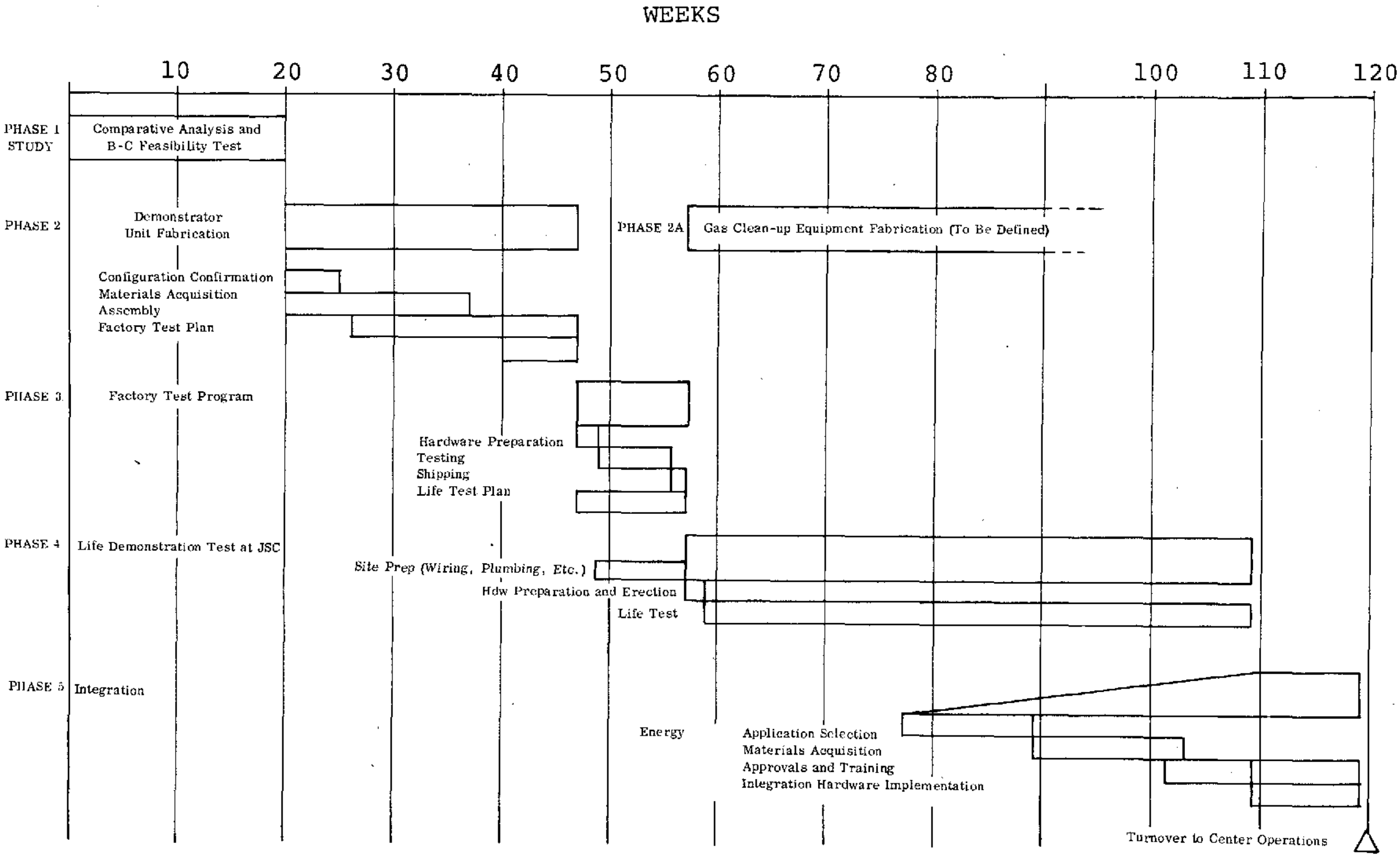
Integration with the energy consumer will overlap the life test demonstration of Phase 4 to assure smooth transition to the JSC operations group in a minimum time after completion of the life test demonstration. Specific application of the product gas would be identified, the interface requirements defined, and interface hardware (ducts, fans, etc.) would be acquired as needed. Those operating approvals which may be required could be obtained in advance and training of JSC operating personnel could be largely accomplished. Erection and installation of integration hardware would then be accomplished, system check-out completed and the entire system could be turned over to JSC operations as a demonstrated item of equipment.

Work Breakdown Structure

The Work Breakdown Structure for the entire Pyrolysis Development Program is shown in Figure 1. The tasks are as described in the Program Approach Section and are reasonably self explanatory.

Pyrolysis Development Program Schedule

The schedule for the Pyrolysis Development Program is shown in Figure 2. The one year demonstration of the hardware dominates the schedule. However, the time required is reasonable and the schedule provides for a well founded overall demonstration of the capabilities of the pyrolysis unit to provide solution to practical solid waste disposal problems concurrent with providing a significant contribution to relieving the energy shortage.



PYROLYSIS DEVELOPMENT PROGRAM SCHEDULE

FIGURE 2

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION

APPENDIX I2

PYROLYSIS DEVELOPMENT PROGRAM TEST PLAN

I2

PYROLYSIS DEVELOPMENT PROGRAM TEST PLAN

Test planning for the pyrolysis development program, as discussed herein, is limited to the recommended vertical-shaft, slagging pyrolysis concept. If current testing of the Barber Colman unit provides results which justify further evaluation of that concept, the further tests should be planned around objectives developed for that approach.

It is Hamilton Standard's belief that the more advanced development status of the vertical-shaft, slagging pyrolysis concept justifies a development test program with the objective of demonstrating the practical readiness and life characteristics of the concept for application in the real world where some dependency upon reliable operation is fundamental to the device's utility. To meet this objective, the test outline presented in Table 1 is suggested in the general case where the gas utilization device with which the pyrolysis unit will be integrated is not specified. In the previous section of this Appendix (Appendix I1, Program Plan) where integration with a boiler is assumed, the Test Objectives were limited to that application.

In this test plan the broader potential applications of the product gas are assumed and integration testing is recommended for a roster of ultimate applications. Hamilton Standard believes this broader testing should be undertaken if funding permits.

TABLE 1

OUTLINE
PYROLYSIS PROGRAM TESTING

PYROLYSIS SUBSYSTEM TESTING

- Energy Recovery
  - Hot Gas
  - Cold Clean Gas
- Gas Composition
  - Gas Constituents
  - Organics, Oil and Gas Carry-Over
    - Out of Reactor
    - Out of Scrubber
  - Particulate Carry-Over
  - Cleanliness of Combustion
    - Out of Reactor
    - Out of Scrubber
- Design Point Size Evaluation
  - Optimum Rate Per Unit Area
  - Rate Variation Capability
- Slag Production Rate
- Refuse Composition Effect On:
  - Energy Recovery
  - Gas Composition
  - Rate Variation
  - Slag Production

TABLE 1 (Cont'd)

Start-Up/Shutdown Evaluation

Operation and Maintenance Evaluation

- Desired Degree of Control Automation
- Major Component Life
- Major Component Maintenance Routine

Coal and Residual Oil Addition to Refuse

- Determine Maximum Percentage
- Determine Modification Required

<u>TESTING OF PYROLYSIS WITH IUS SYSTEM</u>

Gas Utilization Efficiency

- Boiler
- Diesel
- Fuel Cell

Optimize Refuse Disposal/Gas Utilization

- Eight Hour Operation
- 24 Hour Operation
- Peak Matching

Thermal Storage Interface

- Hot Storage
- Cold Storage

Operator Manpower Requirements

- Skills
- Man-Hours

TABLE 1 (Cont'd)

System Integration

- Alternate Modes
- Failure Modes
- Automation
- Alternate IUS Subsystem Compatibility

Testing of the basic pyrolysis unit should follow a classic sequence of functional checkout, confirming normal operation and then an iterative process of varied inputs and operating conditions designed to thoroughly exercise the equipment to establish limits and optimum operating conditions. Only after the basic pyrolysis unit's normal operating parameters are established should variability be introduced to the testing. To this end, initial operation will be conducted around the design point feed rates and operating conditions. The only variations anticipated would be alterations necessary to achieve acceptable operation of the unit.

With this baseline established and a design feed rate and product generation rate established, the next step would be an orderly variation of feed rate and composition directed at establishing the limits of operation in orderly steps. Such important matters as the introduction of various sludges in various percentages, variation in waste material composition and the "salting" of waste material with coal and residual oil needs to be attacked systematically with constant reference to the baseline for subsequent analysis. Only when this brute force testing has been accomplished on the basic unit should peripheral equipment, such as gas clean-up hardware, be introduced to the test.

Applications testing of the product gas can be accomplished at any time after the basic performance of the pyrolysis unit has been established and product gas can be reasonably assured for the conduct of the test. Fumigation of a dual-fuel diesel should be

accomplished if possible. In the time period envisioned for the life test it is unlikely that a fuel cell will be available for extended testing. Such testing should be planned as early as a test article fuel cell appropriate to the test is available. Testing with a boiler burner is sufficiently straight forward that it can probably be accomplished in a real world application after the demonstration tests with an acceptable level of risk.

Throughout the entire test it should be remembered that the fundamental desire is to establish the dependability of the pyrolysis unit for practical application and every effort should be exerted to have the maximum possible total operating time at the end of the test period.

Specific parameters to be recorded and the exact schedule of test to be performed is beyond the scope of this study. However, during the accomplishment of Phase 2 of the Program Plan discusse in Appendix I1, it is important that the specific details of test protocol be mutually established for maximum benefit from the lif test.

APPENDIX I3

PYROLYSIS EVALUATION STUDY GROUNDRULES

I3

PYROLYSIS EVALUATION STUDY GROUNDRULES

BASELINE IUS

- MIUS Preliminary Design Study
- Scale to 1000 Unit Apartment Complex
- Washington, D. C. Location
- Annual Average Climate
- Power Generation-Diesel and Fuel Cell Prime Movers
- Primary IUS Fuel - No. 2 Diesel Oil

SOLID WASTE

Refuse	12000 lb/day
	5000 Btu/lb
	10 lb/cu.ft.
Collection	37.5 cu.ft. wheeled carts
	28 carts/day
	96 carts available (3 day storage)
Sludge	8000 lb/day
	20% solids
	5000 Btu/lb dry solid

WASTE COMPOSITION

	REFUSE	SLUDGE	AVERAGE
H_2O	25%	80%	47%
Inerts	25%	10%	19%
Burnables	50%	10%	34%

HHV (Average) - 3400 Btu/hr

Burnables

87% volatile

13% fixed carbon

10,000 Btu/lb HHV

Combustible Fraction Composition by Weight

53%	Carbon
7%	Hydrogen
38.4%	Oxygen
1.0%	Nitrogen
.2%	Sulfur
.4%	Chlorine

SOLID WASTE SUBSYSTEM

- Duty Cycles

8 hrs/day	7 days/week
24 hrs/day	6 days/week

- System Efficiency = $\frac{\text{IUS Primary Fuel Saved (LHV)}}{\text{Refuse Input Energy (LHV)}}$
- Pyrolysis Hot Gas Efficiency = $\frac{\text{Hot Gas Energy Out (LHV)}}{\text{Refuse Input Energy (LHV)}}$
- Pyrolysis Cold Gas Efficiency = $\frac{\text{Cold Clean Gas Energy Out (LHV)}}{\text{Refuse Input Energy (LHV)}}$
- IUS Engineering and Supervisory Labor Available
- Village Complex IUS
  - Scaled up From 1000 Apartment Units
  - Identical Schematic to 1000 Apartment Units

ECONOMICS

Mid 1974 Washington, D. C. Dollar Base

Economic Life - 20 Years

Fuel - $1.75/ MBTU
- 10%/Yr Escalation
- 15%/Yr Discount

All other costs
- 5%/Yr Escalation
- 15%/Yr Discount

IUS SUBSYSTEM PERFORMANCE CHARACTERISTICS

Power Generation

	Diesel	Fuel Cell
Overall Electrical Conversion Efficiency	33%	40%
High Grade Heat (% of Fuel)	28%	30%
Low Grade Heat (% of Fuel)	17%	20%
Usable Low Grade Heat	0	25%
Losses	22%	10%

Water Chiller - Coefficient of Performance

Absorption	0.67
Compression	4.0

Heat Recovery Efficiencies

Incinerator	60%
Boiler	80%

Cooling Tower Make-up Water

1043 Btu/lb of Make-up Water

APPENDIX I4

EVALUATION CRITERIA FOR SELECTING A PYROLYSIS SYSTEM FOR AN IUS

I4

EVALUATION CRITERIA FOR SELECTING A PYROLYSIS SYSTEM FOR AN IUS

INTRODUCTION

Pyrolysis of solid waste and sewage sludge has the potential for being the best concept for integration with an IUS in order to effectively dispose of these wastes and in turn obtain the benefit of valuable resources such as a fuel gas to offset the energy requirements of an IUS. This discussion presents the evaluation, criteria, and the rationale for selecting these criteria. These criteria are applicable to all Pyrolysis concepts and probably for most other IUS subsystem concept selections, however, only the Barber Colman and the URDC Pyrolysis concepts are of present concern.

SELECTION CRITERIA

Table 1 presents the selection criteria believed to be most appropriate for determining the best Pyrolysis concept for use in an IUS. In addition to the major categories indicated in the table, subcategories are also presented. These categories and subcategories are presented in order of importance as supported by the rationale presented later in this discussion. It is understood that the final criteria and ranking of the criteria will be established after review by the NASA.

RATIONALE

Assuming the concepts being evaluated perform the intended function, the economic picture is the driving influence on selecting an IUS subsystem concept. Concepts still in the development stage or which may have other associated risks such as meeting fire, safety, health and anti-pollution regulations will have to first be evaluated on a go-no-go basis, but assuming technical success the ultimate acceptance will be on an economic basis. If technical risks do exist, the economic comparisons can provide the incentive for continuing the development of a concept.

The subcategories under cost are given in the table and do not require further discussion. However, the escalation rate on material, labor and energy, and an appropriate capital discounting rate must be established.

For advanced technology concept such as the two Pyrolysis concepts being considered, technical risks do exist. The integrational aspects of each concept in an IUS are given in the table. Fuel gas utilization is considered most important. In order to utilize the Pyrolysis feature of energy from waste in the form of fuel gas it is most desirable to burn the gas in the IUS electricity producing prime mover. The most economical IUS electricity producing prime movers are fuel cells and diesel engines.

The effeciency of energy recovery in all forms (electricity, heating, air conditioning, etc.) from the solid waste is considered next in importance. However, if there is a clear and significant saving of IUS primary fuel, efficiency could be the most significant subcategory criteria.

The flexibility to adapt to IUS size variations, IUS supply fuel variations, types of IUS energy needed, waste type variations, waste quantity variations, IUS load variations and 24 hour vs 8 hour waste processing is an important factor in selecting a Pyrolysis concept. The federal, state and local codes and regulations associated with fire, safety, health and anti-pollution must be met by each concept. Each concept will have unique problems associated with meeting these requirements and the associated risks must be evaluated. The complexity of the systems which results from meeting these requirements, and the complexity necessary to perform the intended basic function also is an important evaluation criteria.

The development status of each concept is important in selecting an IUS from both a risk standpoint and a schedule planning standpoint. Both demonstration of the basic function and of any unique ancillary equipment to clean the pyrolysis gas, recover materials, meet anti-pollution requirements, etc. is of importance.

Finally, other potential uses of each concept (outside of an IUS) should be considered in selecting a Pyrolysis concept. General refuse disposal utility application, energy recovery unique to a utility and materials resource recovery are very probable applications for pyrolysis. The size variation capability of each concept is of great importance when considering the size range of utility applications. This range extends from the equivalent of a large IUS application in the 10's of tons per day of waste to the 1000's of tons per day as may be required for large cities. Since coal gasification will be an important contribution to the nation's energy requirements, the capability for adding coal to the refuse as well as for coal gasification done in order to obtain a more useful form of energy is of some important when selecting a Pyrolysis concept.

CRITERIAL WEIGHING

Included on Table 1 is the percentage weighing of the major criteria. This weighing will be used to establish a point count by which a system is selected. Neither pyrolysis system will necessarily obtain a maximum score. As a reference, the best commercially available alternate would receive the maximum score. The URDC and Barber Colman Systems will then be assigned a point score to reflect how closely they came to the ideal.

TABLE 1

EVALUATION CRITERIA FOR SELECTING A PYROLYSIS CONCEPT FOR AN IUS

CRITERIA	WEIGHING FACTOR
Cost of Each Concept for an IUS	35%
Total 20 Year Cost	
Capital Outlay	
Operating and Maintenance Expense	
Integration Aspects of Each Concept in an IUS	35%
Fuel Gas Utilization Problems	
Efficiency	
Flesibility	
Fire, Safety, Health and Pollution Problems	
Complexity	
Development Status of Each Concept	15%
Demonstrated Basic Function Performance	
Demonstrated Status of Ancillary Equipment	
Applications of Each Concept Other Than IUS	15%
Refuse Disposal	
Energy Recovery	
Resource Recovery	
Size Flexibility	
Coal Gasification	

APPENDIX I5

WEIGHTING POINT SCORES OF PYROLYSIS CONCEPTS

I5

WEIGHTING POINT SCORES OF PYROLYSIS CONCEPTS

The rationale provided in Section 4.0 of the main text was used to score the two Pyrolysis systems. The results of this scoring are shown in Table 1. A maximum point score was agreed-to for the major categories with the NASA and these major category scores were further divided into a point score for each subcategory. The maximum point score was given to the Pyrolysis concepts only when they were the most ideal solution for the particular category. Otherwise the maximum point score stands for the best projected alternate solution for the category and the Pyrolysis concepts were both down rated. Even with these considerations, the point scoring is highly subjective. It is, however, believed that by evaluating the merits of the two concepts provided in Section 4 of the main text and the references made in this section to specific appendices, the reader will score each Pyrolysis concept essentially the same as Table 1 and will not materially change the total scores.

TABLE 1

DETAIL RANKING OF PYROLYSIS CONCEPTS

CATEGORY	MAXIMUM SCORE	URDC	BARBER-COLMAN
COST:			
20 YEAR	15	14	4
CAPITAL	10	4	3
O&M	10	9	8
	35	27	15
INTEGRATION:			
UTILIZATION PROB.			
DIESEL	5	3.5	4
FUEL CELLS	5	5	5
EFFICIENCY			
DIESEL/24 HOUR	3	2.2	0.9
FUEL CELL/24 HOUR	3	2.3	1.4
DIESEL/8 HOUR	2	1.5	0.6
FUEL CELL/8 HOUR	2	1.5	0.9

TABLE 1 (Continued)

DETAIL RANKING OF PYROLYSIS CONCEPTS (CONTINUED)

CATEGORY	MAXIMUM SCORE	URDC	BARBER-COLMAN
INTEGRATION (CONTINUED):			
FLEXIBILITY			
IUS SIZE VARIATION	1	1	1
IUS FUEL VARIATION	1	1	0.8
TYPE OF ENERGY NEEDED	1	0.8	0.8
WASTE VARIATIONS	1	1	1
24 HOUR VERSUS 8 HOUR GASES	1	0.2	0.2
FIRE, SAFETY AND POLLUTION	5	5	4
COMPLEXITY			
REFUSE HANDLING AND FEEDING	1	0.8	0.2
THERMAL PROCESSING	1	1	0.8
RESIDUE HANDLING	1	1	1
FUEL GAS PROCESSING	1	1	1
SYSTEM CONTROL	1	0.8	0.5
	35	29.6	24.1

TABLE 1 (Continued)

DETAIL RANKING OF PYROLYSIS CONCEPTS (CONTINUED)

CATEGORY	MAXIMUM SCORE	URDC	BARBER-COLMAN
DEVELOPMENT STATUS			
BASIC FUNCTION	10	5	1
ANCILLARY EQUIPMENT	5	2.5	2
	15	7.5	3
ALTERNATE APPLICATIONS			
REFUSE DISPOSAL	3	1.8	0.6
ENERGY RECOVERY	3	2.4	1.2
RESOURCE RECOVERY	3	2.4	2.4
SIZE FLEXIBILITY	3	3	3
COAL GASIFICATION	3	2.4	0
	15	12	7.2
GRAND TOTAL	100	76.1	49.3

APPENDIX J1

ARTHUR D. LITTLE TECHNICAL COMMENTS ON THE BARBER COLMAN AND URDC PYROLYSIS SYSTEMS

J1

TECHNICAL COMMENTS ON THE BARBER-COLMAN AND URDC PYROLYSIS SYSTEMS

Prepared for

HAMILTON STANDARD
DIVISION OF UNITED AIRCRAFT CORPORATION

77558

December 19, 1974

J/a

Arthur D Little, Inc.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

J2

J3

TECHNICAL COMMENTS ON THE BARBER-COLMAN AND URDC PYROLYSIS SYSTEMS

1. SUMMARY

Initially we anticipated reviewing laboratory data for the URDC/Barber-Colman (B-C) systems and implications in the use of such data for a scaled up process design. Unfortunately little such data became available during the course of our assignment. Consequently our comments have become more of a subjective nature based on our experience in handling municipal solid waste, conducting experimental programs, handling of molten metals, scaling up experimental reactors, etc.

While we might have made slightly different assumptions for preparing the mass and energy balances for the URDC and Barber-Colman systems, we do not find the basic premises made by Hamilton-Standard (H-S) unrealistic. We noted that the elemental balances for the Barber-Colman system do not completely close, but we do not think it will alter our conclusions since assumptions used in the B-C design are based largely on judgment which can have a wider potential source of error and we have seen no laboratory data on which to make a better estimate. Although there is some related experience (e.g., Union Carbide Corp. on the URDC system), there is no such back-up or parallel information on the Barber-Colman system except for some limited data as discussed below. Consequently the process design is based largely on our experience/judgment and we feel it imperative to focus on those areas that may jeopardize the pyrolysis process if the design expectations are not met.

As a result both processes should be thought of as in the earliest stages of technology development and will require extensive planning and testing to demonstrate reliable operation and provide sufficient data for capital and operating cost estimates. In balance, we believe that because of complete lack of experience or background in operation of the B-C system on representative MSW that the B-C concept is a higher risk alternative.

The units being considered for MIUS applications are of a size comparable to a pilot plant. Nobody yet has operated a plant for the pyrolysis of refuse, although UCC is presently starting up a 200 ton/day unit. Consequently, the unit should be designed with flexibility and easy access. Provision should be made to burn off-specification fuel. Purging at start up and shutdown should be provided to prevent explosions during these periods. Fire fighting should be provided both inside and outside of the equipment. Heat losses are always a problem in small equipment and this is particularly true when handling slag. Finally, adequate instrumentation should be provided to allow obtaining good data for design purposes.

J4

2. FEED MATERIAL TO THE URDC AND B-C SYSTEMS

For the small systems being contemplated, feed to the process must be carefully selected by size. Separate provision should be made for handling bulkier items such as white goods (e.g., stoves, refrigerators, etc.) bicycle frames, mattresses, tires, rugs, etc. Thought should be given as to how such bulkier items are to be handled in an integrated utility system. We believe and concur with H-S that resource recovery of metals, paper, and glass, except by source segregation by the homeowner is impractical at this size of operation and also inconsistent with the philosophy of the process selected.

As seen in Table 1 a design criteria of 10,000 Btu/lb of combustibles has been established for evaluation of the pyrolysis systems being studied by NASA. Although we agree that it is reasonable to establish a common design basis to permit the evaluation of several systems and the 10,000 Btu/lb is a reasonable value to choose, we believe it would be prudent to make certain that the systems would be workable if this value turned out to be less. There is a great deal of data to suggest that the heating value of refuse is nearer 9,000 Btu/lb than 10,000.

One method of calculating the heating value of refuse is:

$$HHV = 141 (\% C) + 610 (\% H - \% O/8)$$

Using this equation the combustible fraction proposed in Table 1 would have a heating value of 8815 Btu/lb.

JS

TABLE 1

STUDY GROUND RULES FURNISHED BY HAMILTON STANDARD

Solid Waste

Refuse	12000 lb/day 5000 Btu/lb 10 lb/cu.ft.
Collection	37.5 cu.ft. wheeled carts 28 carts/day 96 carts available (3-day storage)
Sludge	8000 lb/day 20% solids 5000 Btu/lb dry solid

Waste Composition

	REFUSE	SLUDGE	AVERAGE
H_2O	25%	80%	47%
Inerts	25%	10%	19%
Burnables	50%	10%	34%

HHV (average) 3400 Btu/lb

Burnables

87% volatile
13% fixed carbon

10000 Btu/lb HHV

Burnable Composition by Weight

53%	carbon
7%	hydrogen
38.4%	oxygen
1.0%	nitrogen
.2%	sulfur
.4%	chlorine

J6

Work done by E. R. Kaiser and reported in the 1966 Proceedings of the National Incinerator Conference report higher heating values on a dry and ash-free basis as shown in Table 2.

Another source reported the higher heating value for wood on the same basis to be 9000 Btu/lb.

As a result a heating value of 10,000 Btu per pound of combustibles (3400 Btu per pound of wet feed material as shown in Table 1) is not unreasonable, but it could easily be 20% lower. This could affect URDC gas quality by reducing the gas heating value from 140-150 Btu/Cu.ft. to possibly 110-120 Btu per cu.ft. as shown in Table 3. The consequences of such a gas quality should be realistically assessed as to how it may affect the rest of the system components.

Estimates in Table 1 of moisture and inerts content as well as the properties of the sludge seem reasonable.

3. OFFGAS HANDLING IN THE URDC AND B-C SYSTEMS

Lack of operating data on the small units being contemplated precludes making judgments on how high melting pyrolysis tars would behave in the offgas ducts. It has been our experience that burning of newspapers may cause a build up of carbonaceous materials and obstruct the offgas ducts. Such problems would be aggravated in small duct work to be found in pilot plant units where heat losses would be undoubdedly considerably higher. Consequently we recommend that the gas ducts leading to the gas cleaning/quench system should be oversized and easy to clean. Tars and particulate will accumulate in the duct requiring frequent cleaning.

J7

TABLE 2

HEATING VALUES OF MATERIALS TYPICALLY FOUND IN MSW

Material	Higher Heating Value Btu/#
Newspaper	8603
Corrugated Board	7825
Waxed Milk Carton	11871
Junk Mail	7339
Vegetable Food Wastes	8359
Leather Shoe	9681
Lawn Grass	8449

J8

TABLE 3

ESTIMATED HEATING VALUE (LHV) OF URDC GAS

Assumed Higher Heating Value of Combustible on a Dry and Ash Free Basis (BTU/lb)	Gas Quality (LHV) BTU/Cu.Ft.
10,000	∿ 139
9,000	∿ 120 - 130
8,000	∿ 110 - 120

J9

Other items of concern with respect to offgas handling include:

- Care should be taken in the selection of the precipitator for the URDC system--we are not aware of much experience in handling tars in such equipment. Provision should be made for frequent cleaning.

- Attention should be given to the re-introduction of the tars into the reactor. Since this system will be prone to plugging, easy cleaning should be provided.

- It is difficult to predict the corrosive conditions in this system. Care should be taken in the selection of materials in the entire gas handling circuit. Garrett reports the tars are acidic and require materials other than steel for construction. Materials such as reinforced fiberglass, plastics and rubber are corrosive resistant but very temperature sensitive. Stainless steels may be adequate but there is little data to make such a judgment.

- Condensation of tars in wasteheat boilers from countercurrent fixed bed reactors such as Lurgi gasifiers is practiced industrially. However, in reactors processing MSW, the elutriation of fine particulates may be a problem, even at low gas velocities. Such particulates can be expected to increase the handling problems of such tars.

J10

- Even though attempts are made to operate at balanced draft, leakage will be a problem. Air leaking into the system could cause an explosion hazard and gases leaking out will be wet, corrosive and odorous. Joints and seals will be a continuous maintenance problem.

- The fuel gas will most likely be odorous, particularly, with the addition of the sludge. Sludge drying at low temperatures, such as may occur in the top of the bed (URDC or B-C) has been a problem in the past. We have no data on the distribution of such odors when the fuel is burned. Generally, residence times of 0.1 - 0.5 seconds at 1500°F have been suggested for odor elimination.

- Ventilation of the process area will be necessary and the use of that air, for combustion in the air heater for example, should be given serious consideration--outside venting could cause odor or particulate control problems.

4. FUEL GAS HEATING VALUES

With respect to properties of the Fuel Gas from the URDC system, we noted that:

- The overall energy balance as prepared by Hamilton Standard appears reasonable.

J11

- The composition of the fuel gas is high in CO and low in CO_2 in our opinion which would mean that we would estimate a little more fuel gas produced at a slightly lower heating value (see Table 4).

- The heating value of the fuel gas produced can be as high as the 140 to 150 Btu's per cubic foot (CF) estimated by H-S and ADL. However, to allow for upsets, such as gas by-pass and leakage, we would advise the design to be able to accommodate lower (down to 100 Btu's/CF) heating values if possible.

- Comment has been made that ferrous oxide (FeO) aids in slag fluidity in the URDC system which in our experience is true. If the metal in the waste (about 4.8% in the waste fed to the unit) is oxidized, about 0.014 lbs O_2 and 0.046 lbs N_2 will have to be added to the reactor. This will increase the N_2 in the fuel gas by about 7 percent on a weight or mol basis and reduce the heating value 3-5 percent.

With respect to properties of the fuel gas from the B-C system, we noted:

- The Hamilton Standard's assumed composition of the fuel gas without char oxidation is consistent with the pyrolysis gas compositions obtained from Garrett and USBM work (see Table 5).

J/2

TABLE 4

DATA COMPARING UCC AND GAS COMPOSITION

		Process	
	UCC	URDC	
		H-S Estimate	ADL Estimate
Fuel Gas Analysis			
Dry & N_2 Free Composition (Mol %) CO	49.5	58.2	50.6
H_2	29.0	31.6	30.2
CO_2	15.7	6.8	14.8
CH_4	4.8	2.0	3.8
C_2+	1.0	1.4	0.6
N_2 (and O_2) in Dry Fuel Gas (Mol%)	0.3	51.7	52.0
Moisture in Wet Fuel Gas (Mol%)	48	39	39
Heat Value of Fuel			
Dry, N_2 and O_2 Free Fuel Gas (CF/lb waste)	11.10	6.85	7.04
Dry Fuel Gas (CF/lb waste)	11.13	14.18	14.66
HHV of Dry, N_2 and O_2 Free Fuel Gas (Btu/CF)	319	331	308
HHV of Dry Fuel Gas (Btu/CF)	318	160	148
LHV of Dry, N_2 and O_2 Free Fuel Gas (Btu/CF)	298	312	289
LHV of Dry Fuel Gas (Btu/CF	297	151	139
Thermal Efficiency			
HHV Basis (%)	60.1 - 68.9	66.7	63.8
LHV Basis (%)	63.1 - 73.4	79.7	75.8
Properties of Waste (Wt%): Combustibles	58.2	34.0	34.0
Moisture	23.2	47.0	47.0
Inerts	18.6	19.0	19.0
Heating Value of Waste: HHV (Btu/lb)	5820 - 5140	3400	3400
LHV (Btu/lb)	5242 - 4505	2680	2688
lb Oxygen/lb waste	0.22	0.182	0.200

TABLE 5

DATA COMPARING

B-C Gas Compositions (no char recycle) with USBM

and Garrett Data

(mol percent)

Component	Char Oxidized (1) H-S with air oxidation of char	NO AIR OXIDATION OF CHAR (2) ADL calculation on Col(1) upon eliminating air introduction and char oxidation*	(3) Garrett process 900-1000°F	(4) USBM process 1380°F
N_2	46.2	--	--	--
H_2	13.4	35.8	10.5	30.8
CO	15.4	19.3	42.0	15.6
CO_2	15.7	20.1	27.0	18.4
CH_4	6.1	16.3	5.9	22.5
C_2's	2.7	7.2	4.5	9.6
C_3^+	0.5	1.3	8.9	1.5

* Based on the relationships:

- $C + 0.75\ O_2 \rightarrow 0.5\ CO + 0.5\ CO_2$
- All of nitrogen is from air
- Mols oxygen for char oxidation = 0.266 mols nitrogen

- Based on available data on pyrolysis with little air inleakage in a once through system (Garrett and USBM test work) we believe that Hamilton Standard's assumptions on gas composition and char residue (about 4% of wet MSW feed) are not unreasonable.

- We have seen no data and can find no supporting evidence on the reactions occurring (if any) with char. H-S has shown (and we agree) that with air oxidation of the char the gas will contain considerable nitrogen. We suspect that the kinetics of the char water reaction will be slow at 1300°F.

- With the continuous feeding of MSW, sewage sludge, and recycle char into the reaction zone, we would anticipate considerable air being introduced with the MSW or by inleaking air into the reactor which because of its size has a high surface to volume ratio. (If operated at a slight positive pressure, odor problems can become a major source of concern as discussed earlier.)

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5. PROCESS DESIGN PARAMETERS

Regarding URDC Process Design Parameters, we believe that:

- Pretreatment is not required in the URDC system, but we believe gross shredding (about 3-5 kwh/ton of material shredded) would improve the feeding properties and flow characteristics of the wastes and gases in the bed.

J15

- The ram will be prone to plugging--the design should provide for a technique to remove jams easily and hopefully with the unit operating--gas sealing could be a problem in this regard.

- Considering the small size of the pyrolysis unit the bed may bridge during operation and provision should be made to break such bridges as temperatures may climb or gases short circuit through the bed. Such short circuiting can lead to a decrease in the heating value of the product gas.

- Introduction of the air and removal of the slag can be difficult maintenance problems. Provision should be made to clean ports and remove frozen slag. At this size continuous slag tapping may be a problem and batch tapping may be preferred.

- Care should be given to the introduction of the air to assure good distribution at the base of the bed.

- Refractories will flux away at the base of the gasifier--refractory repair or replacement should be an easy, quick job which means careful initial design.

- The sludge should be introduced into the bed uniformly over the entire cross-section to assure good gas distribution and prevent local overwetting.

J16

With respect to B-C Process Design Parameters, we think that:

- As with the URDC system, pretreatment of the solid waste seems to be not only desirable but essential for B-C system in order to obtain a sufficiently uniform mass to allow for reliable heat transfer from the lead bath or radiant tubes to penetrate the waste on the lead hearth. Expected residence times for 6" thick layer on the hearth are expected to be quite long as calculated in Addendum A.

- Pretreatment in the Barber-Colman system consists of shredding to a reported estimated particle size of 1/2" and then compaction as the material is fed into the pyrolysis furnace. Extensive work has been done estimating the power requirement for the shredding of municipal solid waste. Work from two sources is summarized in Figure 1. The results of this work show that about 60 HP hours per ton will be required to shred municipal solid waste to an average particle size of 1/2". It is important to recognize that data on average particle size may be of limited value; a more important value is the largest particle size which could be tolerated in the Barber-Colman system.

  It is difficult to comment on the size of the shredder required for the Barber-Colman process because it depends greatly on the character of the refuse to be shredded. If larger items

J/7

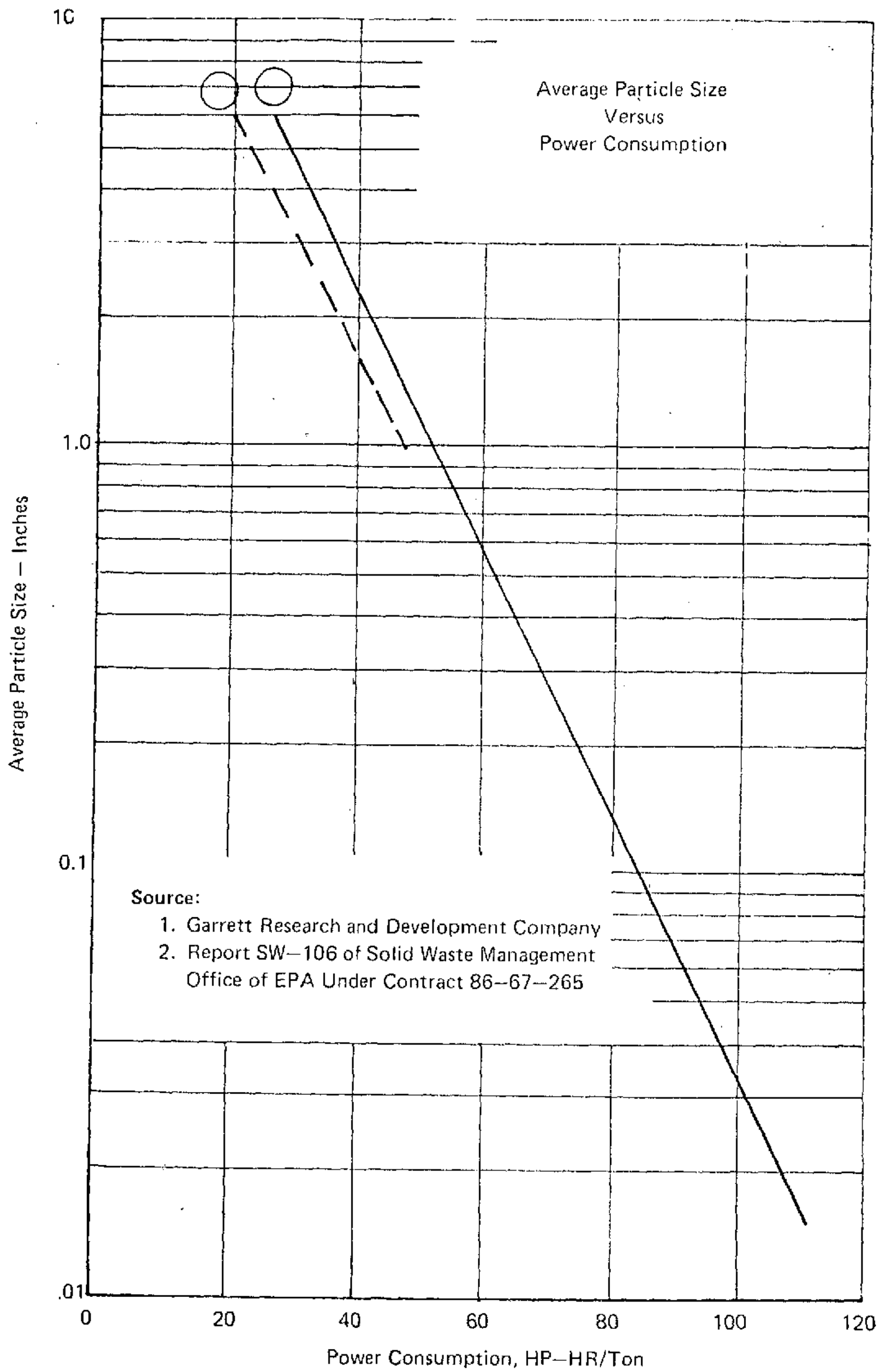


FIGURE 1 SIZE REDUCTION OF MUNICIPAL SOLID WASTE

J/18

are to be fed to the shredder, such as bicycle frames and the like, the shredder has to physically be large enough to accommodate feeding of such materials. Further, if materials such as carpets are to be permitted into the system, the horsepower requirements to handle these difficult items would be much greater than the average requirements when shredding mixed municipal solid waste. Consequently, the physical dimensions of the mill are to be dictated by the largest material to be shredded and the power requirements by the most difficult item which the shredder is anticipated to handle.

- Experience to date on shredders has indicated that hammer wear is a very large maintenance item. Most shredders in operation to date will operate for approximately 16 hours at its average design capacity and then be down for 8 hours for hammer refinishing. Newer designs call for rotors which are reversible and have impact cages which are adjustable. It is anticipated that such mills will be able to operate longer periods without hammer refinishing. However, we do not know the availability of such shredders on a scale as small as that anticipated by NASA. Certainly the investigation of such shredders for this service would appear advantageous.

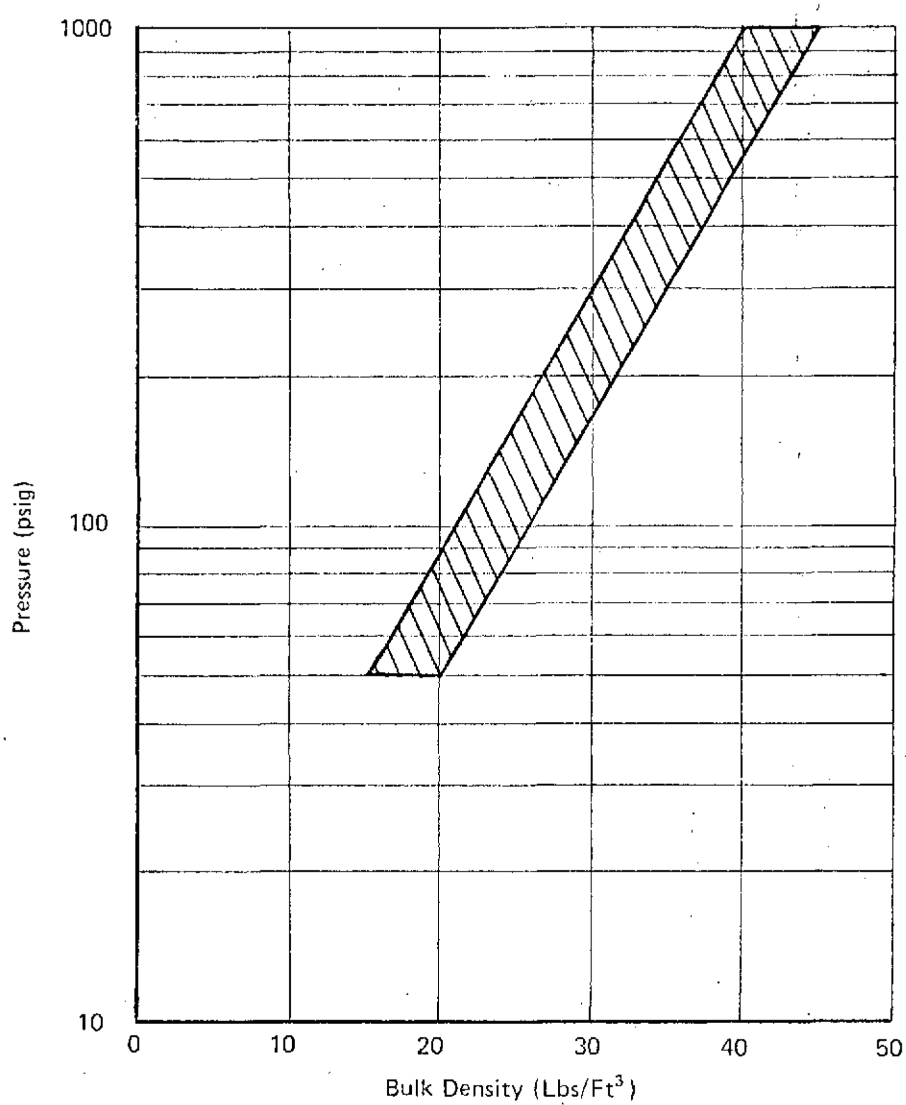
- The handling of municipal solid waste in its raw or shredded form in such things as rams and screw conveyors has proved troublesome. It is our opinion that great care should be given in the selection of the feeder/compactor proposed by Barber-Colman.

- We have conducted experiments to estimate the bulk density of shredded material as a function of its compaction pressure after removal from the mold and this data is presented in Figure 2. This data suggests that compaction pressures from a low of 160 to a high of 1000 lbs/cu. in. will be required to compact municipal solid waste shredded to -1/2" to a bulk density of from 30-40 $\#/ft^3$. We are not aware of any equipment which is currently used routinely to perform this service, although we do understand that some work is being done on pelletizing a shredded, classified municipal solid waste. As a result, we believe it is mandatory to demonstrate the workability of such a piece of apparatus before application in a pyrolysis system.

- Our experience indicates that before making further commitments on the B-C concept, it would be highly desirable to make a detailed calculation and possibly experimentally test the concept of being able to transfer sufficient heat into the solid waste within a reasonable residence time. (Parameters to be investigated should include heat transfer rate as a function of source temperature, MSW density and moisture content).

- We understand that the B-C molten lead hearth concept has been tested so far only on cow dung which is a fairly consistent material compared to other solid waste. We think it highly desirable to further test the B-C concept on solid waste to be actually anticipated in order to determine the effect of a non-

J20



Source: Arthur D. Little, Inc.

FIGURE 2 BULK DENSITY OF SHREDDED MUNICIPAL SOLID WASTE AFTER REMOVAL FROM MOLD
Compression Pressure Versus Bulk Density

J21

uniform material and how it flows on the lead hearth. In addition, it would be highly desirable to understand the degree of reaction of chlorides and other impurities creating undesirable gaseous species which may cause ultimate heavy metal pollution problems (e.g., chlorides from plastics creating volatile lead chlorides, tin chlorides (tin from cans), iron chlorides such as $FeCl_3$).

- Careful consideration should be given to the reaction of impurities in the solid waste with the lead bath. Tin and other metals can be expected to dissolve to a larger or lesser extent in the lead and necessitate eventual purification. While such purification is done commercially in lead and tin smelters, their scale of operation is economically justified only when handling tens to hundreds of thousands of tons of metal annually.

6. ENVIRONMENTAL CONSIDERATION

Protection of the Environment should be insured. In this regard, we believe that:

- The slag from the URDC system should be inert and be a good fill material. Most likely, it can be used as fill or balast and not have to be landfilled.

- The wastewater from either system will have to be treated for suspended solids, acidity, BOD and COD. These problems should be able to be handled in a sewage treatment plant with primary and

secondary treatment. Too little is known to predict if refractory organics will be formed. Garrett's data suggests a large number of organic materials (acids, aldehydes, alcohols and the like) are found in the water soluble organic fraction. In the B-C system we believe it is unreasonable to expect that all such pollutants can be absorbed by the char. Even if such pollutants as Cl^- were absorbed in the first pass, they would build up in the system if the char were recycled to extinction.

- Noise should not be a problem except possibly for the fans and shredder. These may have to be housed separately or properly baffled.

J23

ADDENDUM A

ESTIMATION OF MINIMUM RESIDENCE TIMES IN THE B-C SYSTEM

In the Barber-Colman it is extremely difficult to reliably estimate expected heat transfer rates from the radiant tubes and lead bath to the MSW. Calculations are here made to estimate maximum transfer rates by assuming what we believe to be realistic bulk densities in the range of 5 to 10 pounds per cubic foot.

While it is true that such a mass may be agitated by steam evolution from the MSW it is still necessary to transfer heat to the MSW. A surface evolving steam tends to hinder heat transfer into the mass and thus we think the calculational method below will yield optimisitcally short residence times. We start by assuming a case in which :

- water has been evaporated, and thus no heat is required to evaporate water.
- steam evolution has stopped,
- all the MSW material is now at 300°F. ($=t_b$), and
- for pyrolysis it is necessary to raise the temperature of the mid-plane to 900°F ($=t_m$).

J24

- bulk density of the MSW (dry as mentioned above) is 6 to 7 lbs per cubic foot.

- The MSW lies in an even thickness layer on the lead hearth.

The calculational method for determining heat transfer rates into "slabs" is described in many texts (e.g., see McAdams, Heat Transmission, 3rd Ed. p. 36 McGraw Hill, N.Y. 1954) with published results summarized in Figure A-1. Values of thermal conductivity and density are found in McAdams' text and the heat capacities are tabulated in Perry's Handbook for Chemical Engineers. Values for some cellulosic and other materials are shown in Table A-1. Examination shows that a thermal diffusivity of 0.014 ft^2/hr might be expected for materials in the bulk density range of 6 to 7 lbs. per cu. ft. Calculations below are made to determine the residence time for a case having 6 inches of MSW on a lead hearth with MSW density of 6-7 lbs per cu.ft. and thermal diffusivity of 0.014 ft^2/hr.

J25

ROUGH DRAFT

By CLK/1t
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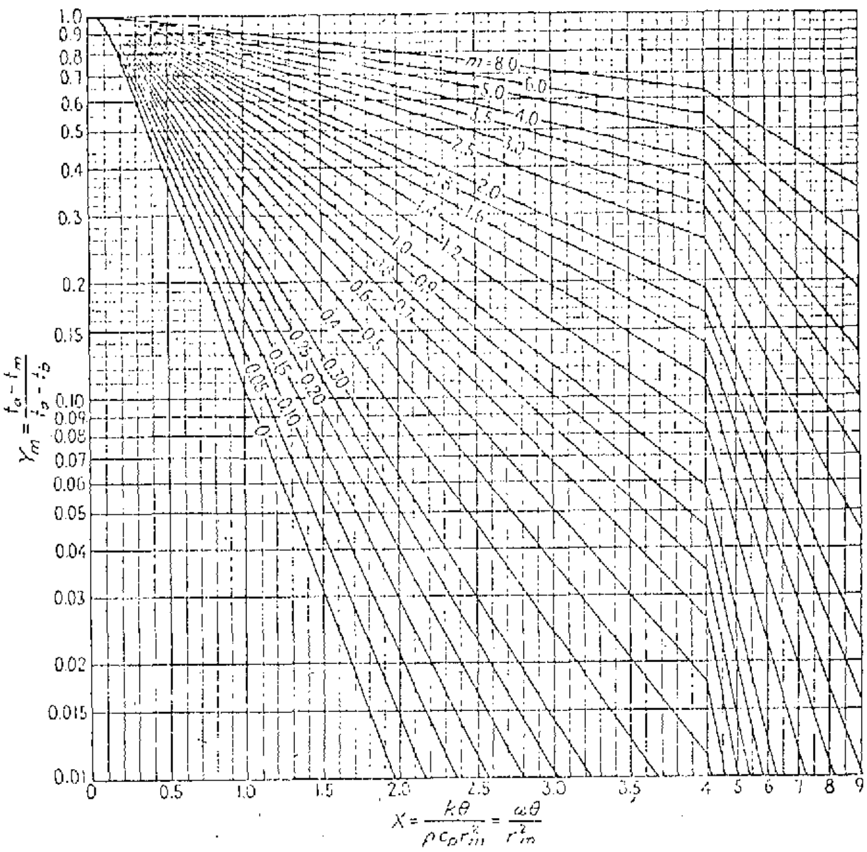

Fig. 3-3. Hottel chart[23] for large slab, for evaluation of midplane temperature t_m.

FIGURE A-1

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J26

ROUGH DRAFT

By CLK/lt

Date

Page 26

TABLE A-1

PHYSICAL PROPERTIES OF SELECTED MATERIALS EXPECTED TO BE FOUND IN MSW

Material	ρ Density (lbs/Cu.ft.)	k Thermal Conductivity (BTU/hr-ft-°F)	C_p Heat Capacity BTU/lb°F	$a = k/\rho C_p$ Average Thermal Diffusivity ft^2/hr
Cotton	5.0	0.039	-	-
Silk	6.3	0.034	0.330	0.016
Wool	8.5	0.033	0.325	0.012

J27

Calculational Method

Using the nomenclature of Figure A-1 the unaccomplished midplane temperature difference, Y_m, is calculated based on the following assumptions:

- Radiant burner temperature, equal to 1650°F and lead hearth at 1300°F.
- Initial MSW temperature t_b = 300°F.
- The MSW surface, t_a, comes immediately to a temperature of 1475°F, a temperature midway between the radiant burners at 1650°F and lead hearth at 1300°F. For this case of infinitely fast response of the surface to a temperature of 1475°F, the parameter m is zero.
- To accomplish pyrolysis assume a temperature of 900°F is needed and thus the midplane MSW temperature (center of 6" thick layer) is to be 900°F = (t_m).
- r_m is 0.25 ft and is one-half of the layer thickness. It is the distance from the surface of the MSW to the center (midplane) of the 6" thick MSW layer.
- Consequently Y_m defined in Figure A-1 is calculated to be (1475-900)/(1475-300) = 0.49.

- At this value of Y_m Figure A-1 shows X is about 0.35 when m=0.

- Based on the above assumptions and values calculated above the residence time Θ to bring the center of the MSW layer to 900°F is calculated from:

$$\Theta = X\, r_m^2/\alpha$$

$$= 0.4\ (0.25)^2/.014$$

$$= 1.56 \text{ hours}$$

When treating 20,000 lbs of wet waste per day (10,600 lbs of dry solids; (see Table 1), the consequence of such a long residence time is to make a large hearth area as seen by the following calculations.

- assume 6.5 lbs/cu.ft. of dry solids,

- volume, V, treated in residence time of 1.56 hours:

$$V = \frac{10,600}{6.5}\ \frac{1.56}{24}$$

$$= 106 \text{ cu.ft.}$$

J29

- Hearth area, A, for 6" thick MSW layer

$$A = 106/(0.5)$$
$$= 212 \text{ sq.ft.}$$

Such a furnace may have unreasonably high heat losses per ton of MSW unless the furnace is well insulated.

Caution of course should be used in applying such a theoretical analysis to unhomogeneous material as MSW. However, since we have neglected the water to be evaporated in the above calculations, we do believe that there is cause to be concerned about being able to transfer heat to the bulk of the material and attention should be paid to this problem in any experimental program.

J30

APPENDIX J2

URDC CONCEPT SUPPORTING TEST DATA

A SUMMARY OF SOME EXPERIMENTAL DATA RELEVANT TO THE DESIGN OF FIXED BED GASIFIERS FOR SOLID WASTE PROCESSING

Prepared by K. T. Lear Associates
as a supplement to the
Pyrolysis System Evaluation Study

December 30, 1974

J32

P.O. Box 288 53 Lyness Street Manchester Connecticut 06040 (203) 647-9795

K. T. LEAR ASSOCIATES, INC.

INTRODUCTION

This supplement has been prepared by K. T. Lear Associates in order to provide the NASA with more detailed background information on the experimental basis for the design of fixed bed gasifiers for processing municipal solid wastes.

It should be noted that this summary is by no means complete although it does include the major portion of what K. T. Lear Associates considers the best available numerical data for air gasifiers. Much of the very crucial available design data is in the form of knowledge of configuration and design details that will or will not work in a particular situation. The acquisition of this kind of very practical - - and very necessary - - design information is often painful, and certainly quite time and money consuming. Without it successful system design and operation cannot be achieved.

Another class of crucial design information not covered in this supplement is the understanding of basic process mechanisms. Enough work has been done in this area to give sufficient insight into the processes involved to allow rational predictions of the effect of changes in operating conditions. This has been particularly important for the IUS study since the bulk of the available operating experience has been obtained with residential refuse rather than the sludge/refuse IUS mix.

This report also does not cover work done by other companies in the field. Both Union Carbide and Torrax have had considerable relevant experience. Some published as well as unpublished data is available and makes a quite valuable supplement.

J33

BACKGROUND

The history, general experience, and some data from the URDC pyrolysis programs through September of 1971 are given in some detail in Ref. 1 and will not be repeated here. Basic technical responsibility for the development programs at URDC during this time period was held by personnel now principals of K. T. Lear Associates. Pilot plant programs included first a five foot diameter gasifier with a nominal capacity of 1 ton/hr, and finally a 16 inch diameter gasifier with a nominal capacity of 140 lb/hr. The bulk of the numerical data came from the latter program.

Since 1971 URDC has built and operated a much larger facility. However, K. T. Lear Associates personnel have had no connection with URDC since 1971.

J34

EXPERIMENTAL TECHNIQUE

A schematic of the 140 lb/hr pilot plant, taken from Ref. 1, is reproduced here for convenience as Fig. 1. The feedstock was all residential refuse collected by project personnel as put out for disposal by the householder. The only major bias in the collection was that only bagged refuse could be taken. However, since most householders put out their waste either all in cans or all in plastic bags, taking only bags still gives a good representation of typical mixed residential solid wastes. The only other selection was the avoidance of bags containing exclusively grass clippings, leaves, or other yard wastes. Physically large objects also were avoided.

The feeding procedure was to fill the gasifier and feed chute to the top with an initial weighed feeding. The feed chute then was refilled to the top with weighed amounts of refuse at approximately 15 minute intervals. No prior mixing or sorting of refuse could be attempted since the only way the waste could be weighed or handled was in the original refuse bags. The only separation practiced was the removal of any overly large objects that were noticed as the bags were emptied into the feed chute. The average amount of waste fed per run was 750 lb.

Slag tapping was intermittent since the average slag flow was too low to provide sufficient thermal inertia to keep the slag tap open. The tap was sealed between pours with a plug of lightweight refractory "mud". The total slag flow was weighed after completion of a run.

The first priority for most runs was to demonstrate the process to a visitor. The acquisition of design data was a secondary goal. Since many hours were required to insure that the system had reached something approximating steady state operating conditions, each run only could represent a single operating condition. Therefore gasification air flow and temperature usually were set at conditions close enough to previous experience to insure a successful run. The only control modifications during a run were small changes to maintain satisfactory operating conditions. Since gasification air flow was an indirect setting, small changes in flow during the run could result from variations in conditions within the gasifier as well as from conscious control attempts. In no case was any attempt made to attain a specific refuse consumption rate.

Gasification air flow rate was measured by an orifice upstream of the gasification air heater. There was some leakage of air from the system. Attempts were made to correct the leakage by measurement of leakage flow and correlation to pressure.

Temperatures were measured at various points in the system, including the refuse bed within the gasifier. Gasifier temperatures were measured with Chromel-alumel thermocouples inserted through the gasifier wall and projecting slightly into the gasifier. Thermocouple life was quite short in the hot zone. The desire to avoid losing these thermocouples was an incentive to maintaining the gasifier at temperature conditions relatively close to the minimum for the process.

Care should be taken in attempting to interpret these temperature measurements. In the bottom hot zone of the gasifier the environment is strongly radiant and the thermocouple should read the temperature of its local radiant environment. In the cooler upper zone, radiation will be negligible and the thermocouple reading would be much more influenced by local gas temperatures.

Pressures were measured at various points in the system. Pressure taps in the hot zone of the gasifier were subject to plugging by melt. Therefore all gasifier bottom end pressures are quite unreliable and only should be taken as a rough guide for expected pressure levels.

Some gas analysis was done both on the fuel gas produced, and on samples drawn from within the gasifier. The data are given and discussed in the data expansion section of the report (Appendix A2) and will not be repeated here.

J36

EXPERIMENTAL RESULTS

A summary of the basic run history is reproduced from Ref. 1 as Table 1. Average performance data for the individual runs is given as available in Table 2. Detailed data are plotted for the later runs in Figures 2 through 46. These are the original plots made from the raw strip chart data, and are presented as they were drawn. Quality of art work and reproduction are relatively poor since these plots were never intended for formal publication.

J37

ANALYSIS

Considerable analysis has been done. This has led to the development of design parameters as well as an outline of a basic model of the process. This process model has been carried to the point where a computer simulation of the process could be fashioned. The results of the analytical work have been discussed in Ref. 2.

One point that should be borne in mind when examining the data is that the refuse feed was of uncontrolled and unknown composition. The inert content can be approximated by the measured slag percentage. (This is only an approximation since more or less residue was left in the gasifier at the end of any particular run and processed during the next run. As a result the inferred inert content for any specific run could be in error even though the average for a number of runs would be correct.) The composition of the combustible fraction of the refuse probably stays quite constant and can be estimated with reasonable accuracy. The major uncertainty is in the water content of the refuse. Since this is an unknown and cannot be estimated even crudely, the fraction combustibles also was unknown. Refuse water content probably varied over a very wide range. Since this is a variable that is not only unknown but also quite fundamental, any general correlation of the data becomes impossible. This can be seen by an examination of the data.

Some bridging and channeling did occur. Bridging certainly should be expected since the scale of many objects fed into the gasifier (e.g. a quart bottle) was on the same order of size as the gasifier diameter (16"). Bridges if left alone would eventually collapse by themselves, although the performance would be reduced somewhat for a time. The effect of bridging can be seen in some of the refuse consumption plots. See for example Fig. 29, on which a bridging problem was noted.

In a sense the process can be thought of as quite similar to ordinary turbulent flow except that the time scale is stretched out by many orders of magnitude. Small scale channeling, variable in time and space, is a characteristic of the process, and analogous to turbulent fluctuations. The effect can be seen in the temperature profile plots which give both the range and average for temperatures measured in any particular level in the gasifier. In no case during steady state running, was an uncontrolled channel observed

(i.e. a channel that would not close by itself before fuel gas temperatures became excessive.)

Probably the most important single conclusion from this test series is that it was possible to process approximately 30,000 pounds of very ordinary unselected, unshredded residential refuse in a 16" diameter gasifier, without any problems other than those associated with known deficiencies in hardware or auxiliary systems. Since refuse composition is a random variable, the very small batch size used in these experiments reduced averaging and insured that the gasifier processed a very wide range of compositions. Large variations could be expected both from run to run and within any particular run. This is illustrated by the very considerable variations in the percentage of inerts which reached over 40% in several cases.

J39

REFERENCES

1. Eggen, Alfred, and Powell, Orlo A., "Experience in Slagging Pyrolysis Systems," Presented to ASME Incinerator Division Research Committee, Oct. 28, 1971.

2. Eggen, A. C. W., and Kraatz, Ronald, "Gasification of Solid Wastes in Fixed Beds," ASME Paper No. 74-WA/Pwr-10, Nov. 1974.

J40

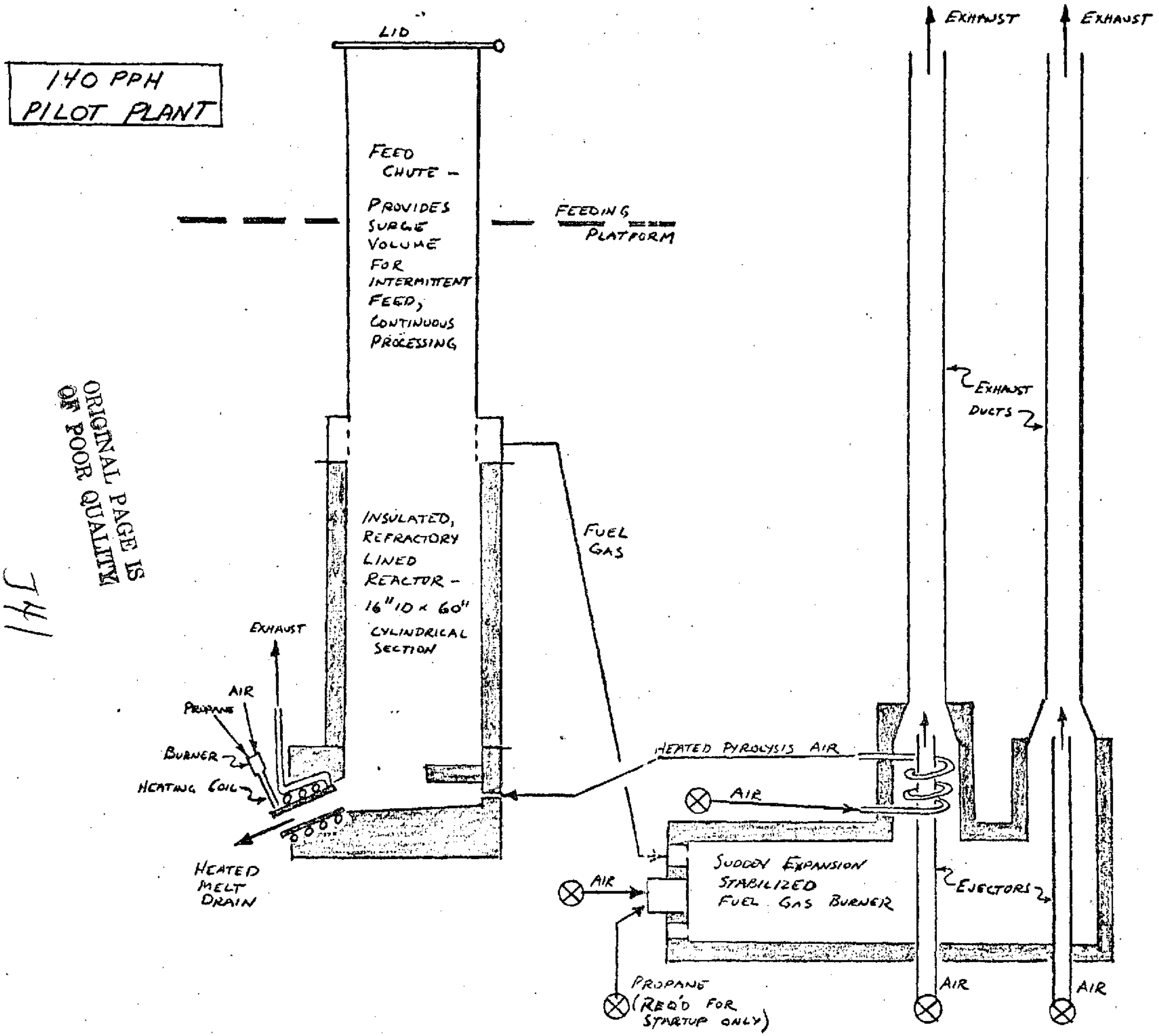

FIGURE 1

741

AF 10-27-71

RUN HISTORY 140 PPH PILOT PLANT

TABLE I

RUN NO.	DATE	REFUSE FED	MELT DRAINED	CUMULATIVE REFUSE FED	CUMULATIVE MELT DRAINED	COMMENTS
1	2/27/71	444 LB	92 LB	444 LB	92 LB	
2	3/2	713	257	1157	349	
3	3/3	622	487	1779		
4	3/4	489		2268	836	
5	3/5	458	240	2726		REACTOR CLEANED OUT - 80LB MELT
6	3/9	779		3505	1156	
7	3/16	327	68	3832	1224	
8	3/18	915	300	4747	1524	
9	3/19	840	211	5587	1735	
10	3/25	631	160	6218	1895	30% AVERAGE MELT
11	3/26	906	234	7124	2129	
12	3/30	2060	501	9184	2815	REACTOR CLEANED OUT - 185LB MELT
13	4/8	820	166	10,004	2981	
14	4/15	908	214	10,912	3147	
15	4/16	513	198	11,425	3393	
16	4/22	786	240	12,211	3633	
17	4/23	790	315	13,001	3948	
18	4/30	972	220	13,973	4168	
19	5/6	642	237	14,615	4405	
20	5/12	626	278	15,241	4683	31% AVERAGE MELT
21	5/14	718	255	15,959	4938	
22	5/25	795	242	16,754	5180	
23	5/26	886	300	17,640	5480	
24	6/2	811	247	18,451	5727	
25	6/3	663	285	19,114	6012	
26	6/14	700	297	19,814	6309	
27	6/28	406	136	20,220	6445	
28	7/1	705	200	20,925	6645	
29	7/16	704	263	21,629	6908	
30	7/20	904	301	22,533	7209	32% AVERAGE MELT
31	7/23	739	314	23,272	7523	
32	7/29	800	239	24,072	7762	
33	8/6	578	105	24,650	7877	10 LB MELT REMOVED FROM REACTOR
34	8/11	689	206	25,339	8083	
35	8/12	1062	277	26,401	8360	
36	8/31	870	250	27,271	8610	
37	9/17	816	285	28,087	8895	J42
38	10/6	674	271	28,761	9166	
39	10/15	538	247	29,299	9413	
40	10/21	608	219	29,907	9632	32% AVERAGE MELT

TABLE 2. AVAILABLE AVERAGE TEST RESULTS

Run No.	Bed Loading	Inerts Drained	Gasif. Air*	Gasif. Air Temp.	Hot Zone Temp.	Fuel Gas Temp.
	lb ref./hr-ft^2	%	lb air/lb ref.	^oF	^oF	^oF
1	61	21				
2	104	36				
3	104	↑				
4	96	31				
5	139					
6	104	↓				
7	143	21				
8	86	33				
9	82	25				
10	68	25				
11	75	26				
12		24				
13	86	20				
14	68	24	1.17	1430	2200	595
15	64	38	1.13	1600	2130	590
16	71	30		1510	2185	660
17	71	40		1500	2270	645
18	79	23	1.0	1525	2220	550
19	61	37	1.25	1500	2350	650
20	57	44	1.11	1500	2200	530
21	59	36	1.26	1450	2340	570
22	64	30	1.18	1260	2260	700
23	82	34	.76	1500	2270	470
24	79	30	.94	1380	2260	630
25	79	43	.89	1420	2190	640
26	83	42	.93	1400	2200	500
27	79	34		1440	2240	510
28	80	28	1.00	1480	2270	590
29	86	37	.82	1470	2250	450
30	82	33		1510	2170	520
31	64	42		1490	2240	550
32	84	30	1.08	1330	2030	790
33	64	18	1.34	1400	2030	690
34	108	30	.85	1450	2030	550
35	109	26	.83	1220	2100	550
36	93	29	.95	1100	2110	
37	100	35	.94	1250	2320	
38	89	40	.93	1300	2360	535
39	84	46	.97	1380	2280	640
40	100	36	.81	1260	2250	590

*corrected for leakage

J43

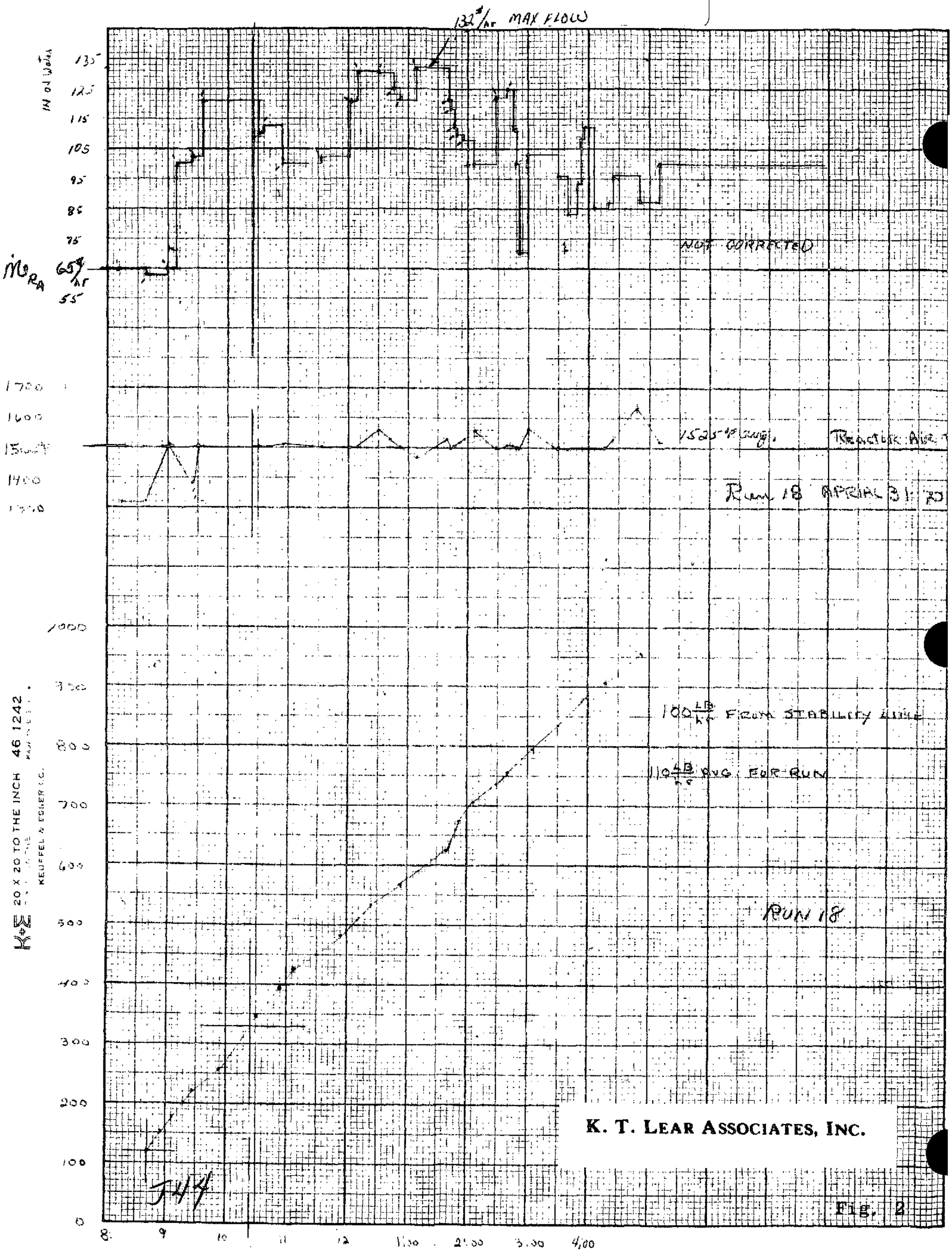
132#/hr MAX FLOW
IN of Water
135
125
115
105
95
85
75
65#/hr
55
NOT CORRECTED
1700
1600
1500°F
1400
1525°F avg.
Run 18 APRIAL 31 '70
1000
800
700
600
500
400
300
200
100
0
100 LB/hr FROM STABILITY LINE
110 LB/hr AVG. FOR RUN
RUN 18
8
9
10
11
12
1:00
2:00
3:00
4:00
20 X 20 TO THE INCH 46 1242
KEUFFEL & ESSER CO.
K. T. LEAR ASSOCIATES, INC.

Fig. 2

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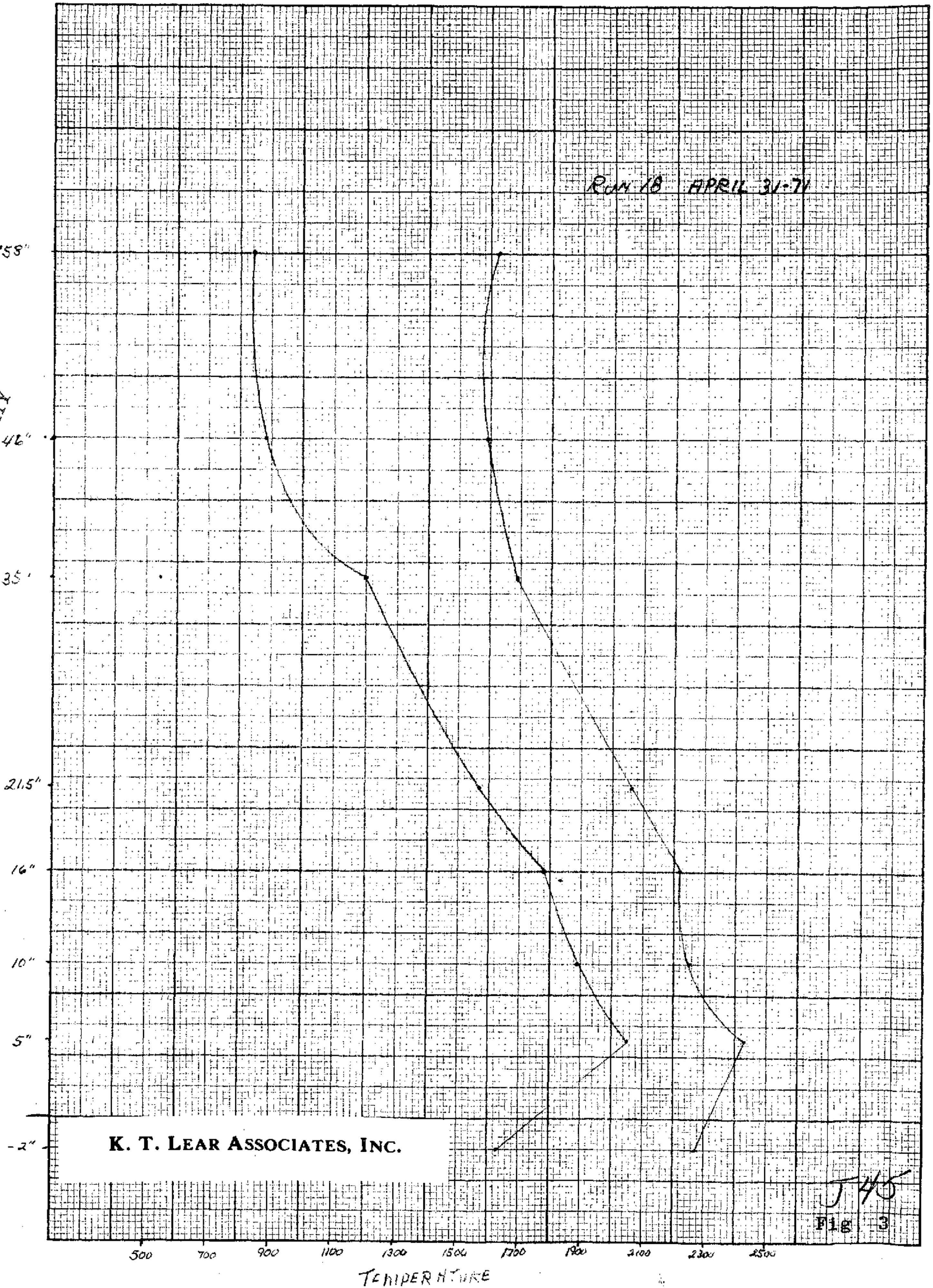
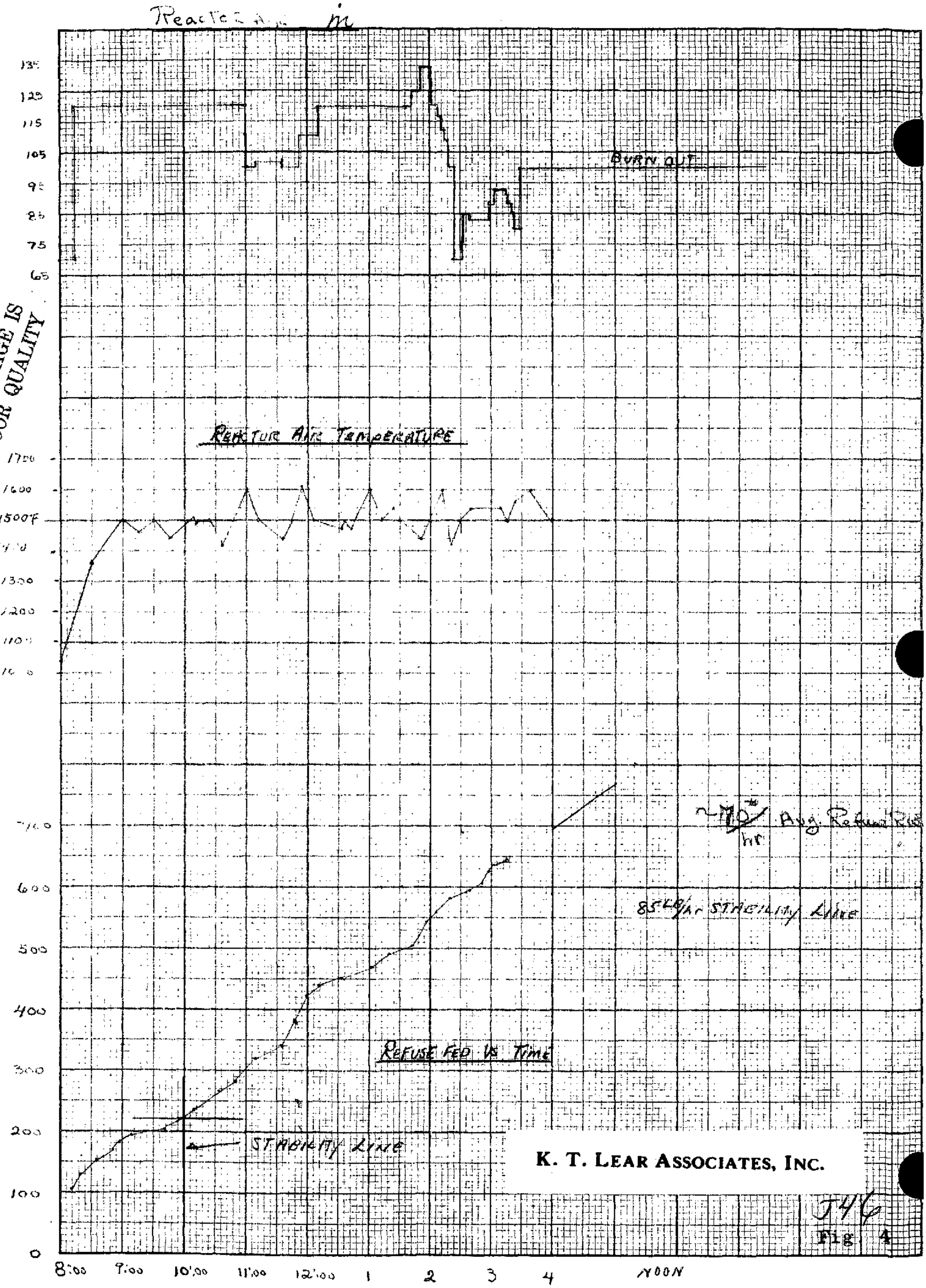


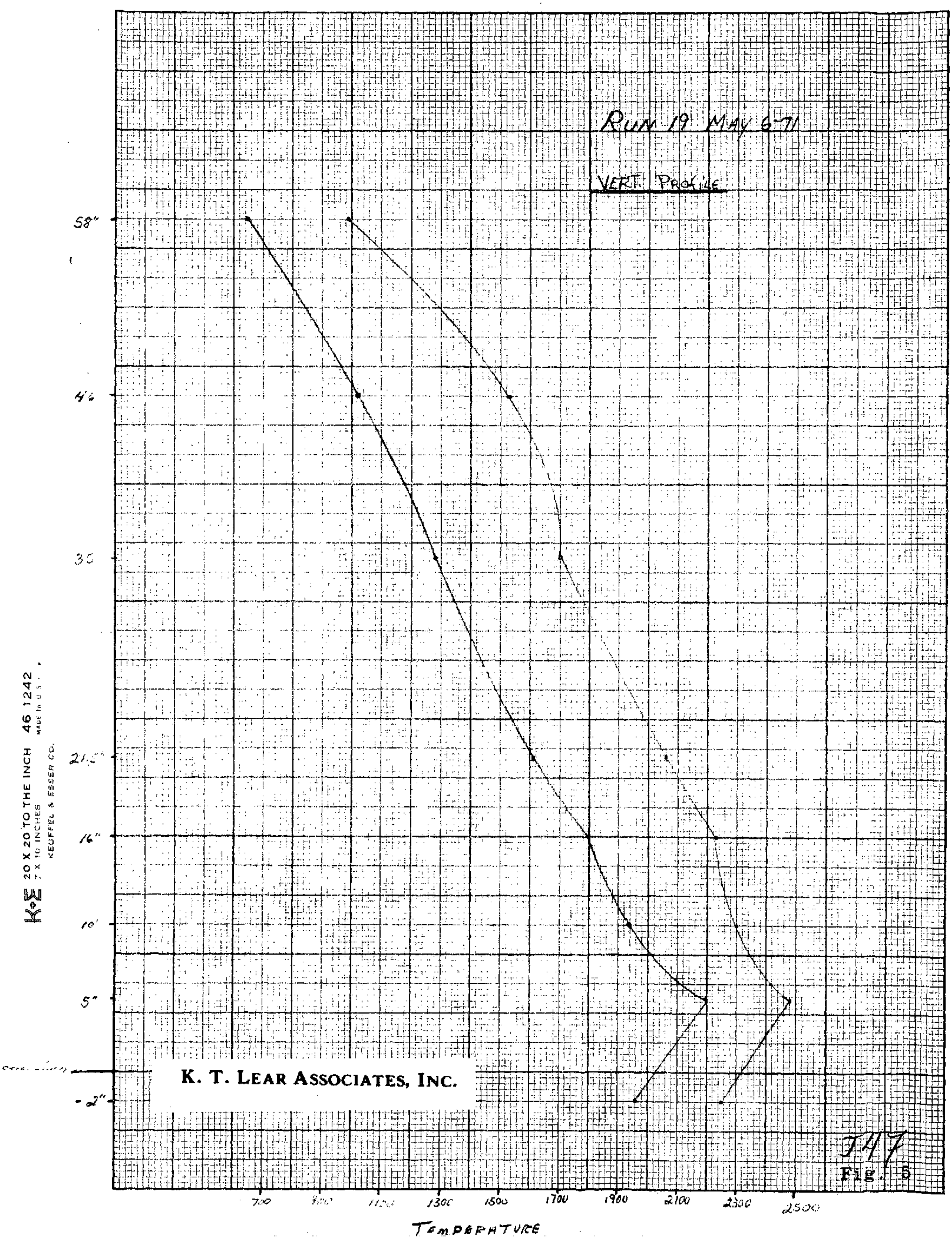
Fig 3



K. T. LEAR ASSOCIATES, INC.

J46

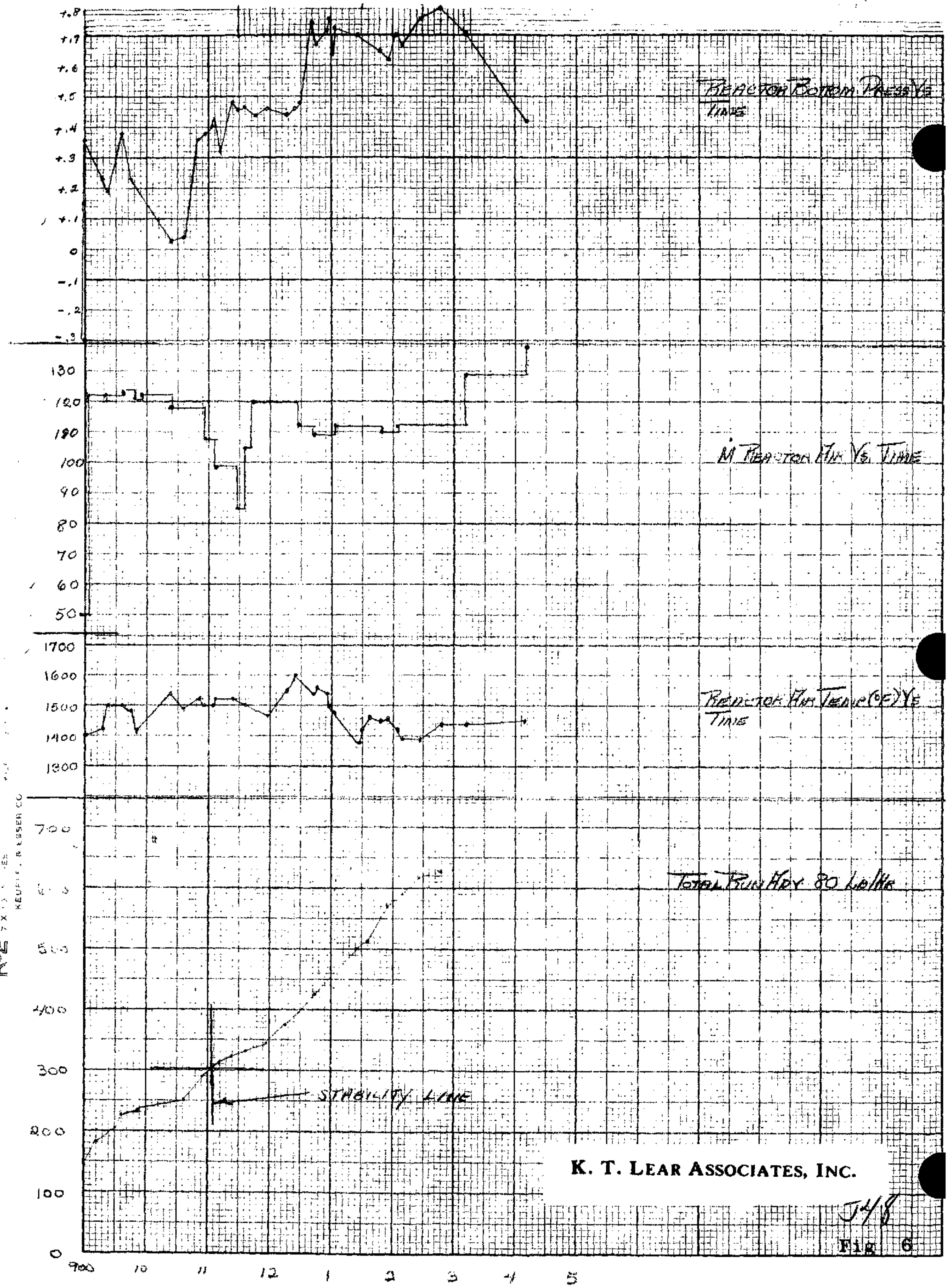
Fig. 4



K. T. LEAR ASSOCIATES, INC.

T47

Fig. 6

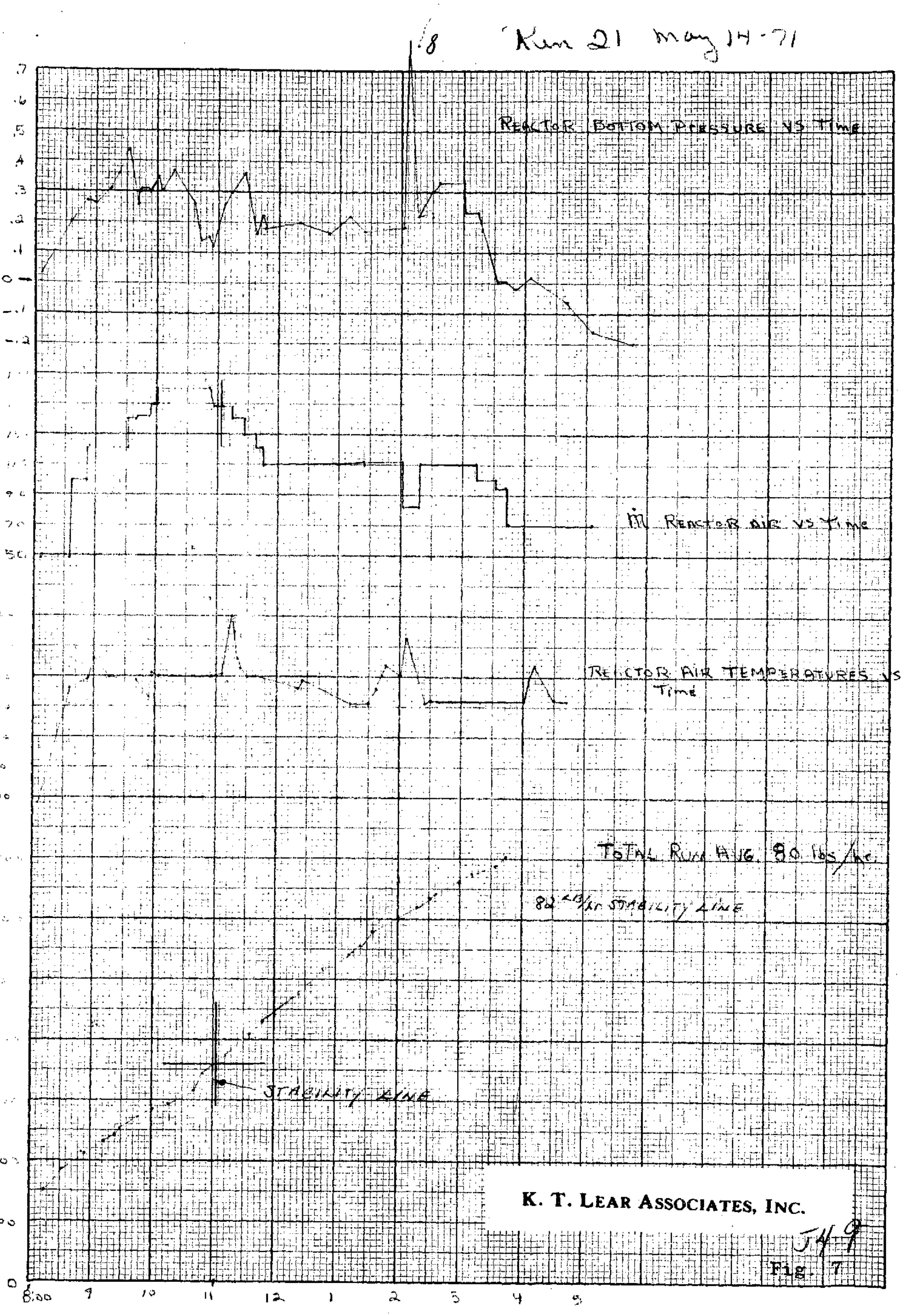


K. T. LEAR ASSOCIATES, INC.

Fig 6

K&E 20 X 20 TO THE INCH 46 1242 KEUFFEL & ESSER CO.

Run 21 May 14-71



K. T. LEAR ASSOCIATES, INC.

JH 9

Fig. 7

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K&E 20 X 20 TO THE INCH 46 1242 KEUFFEL & ESSER CO.

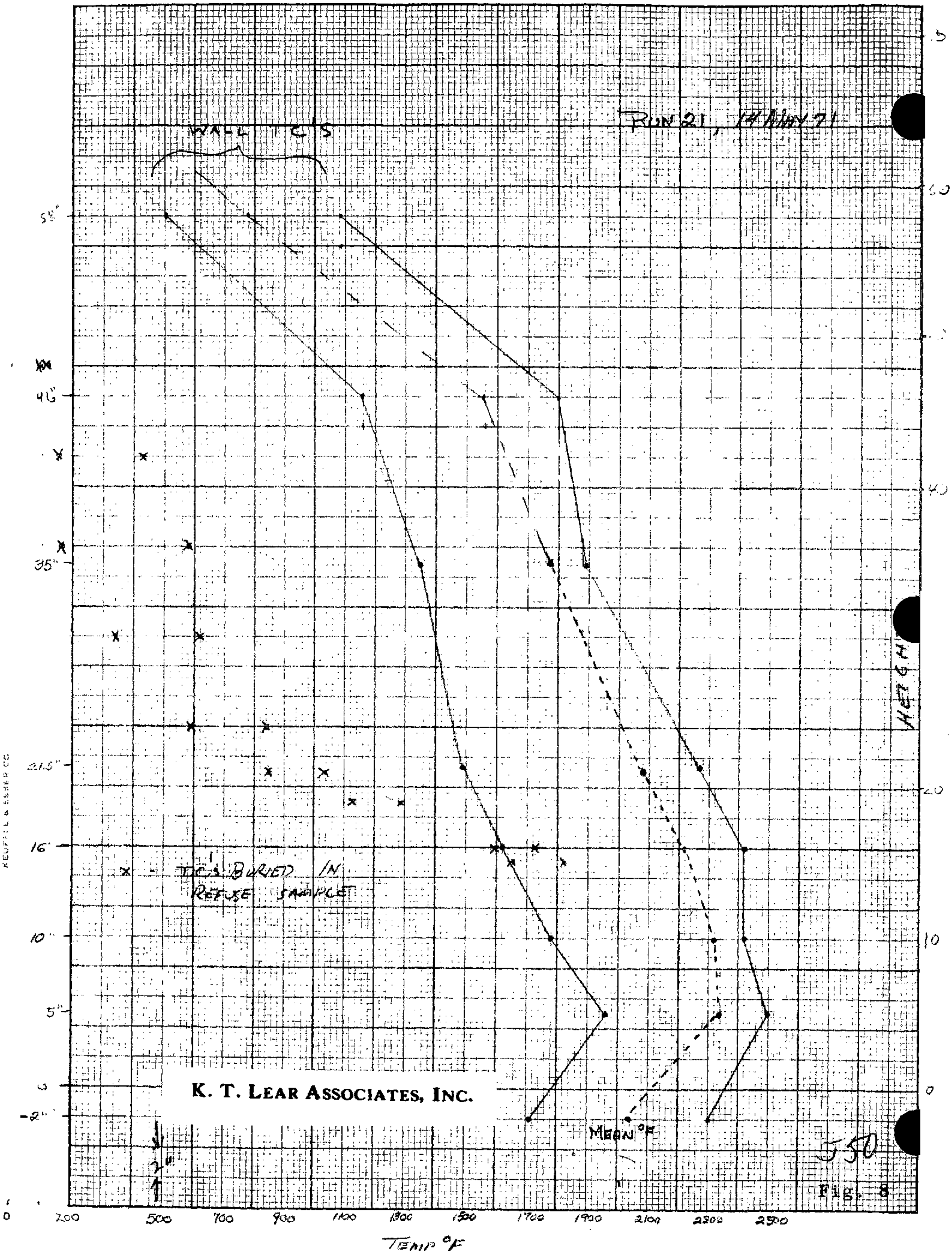
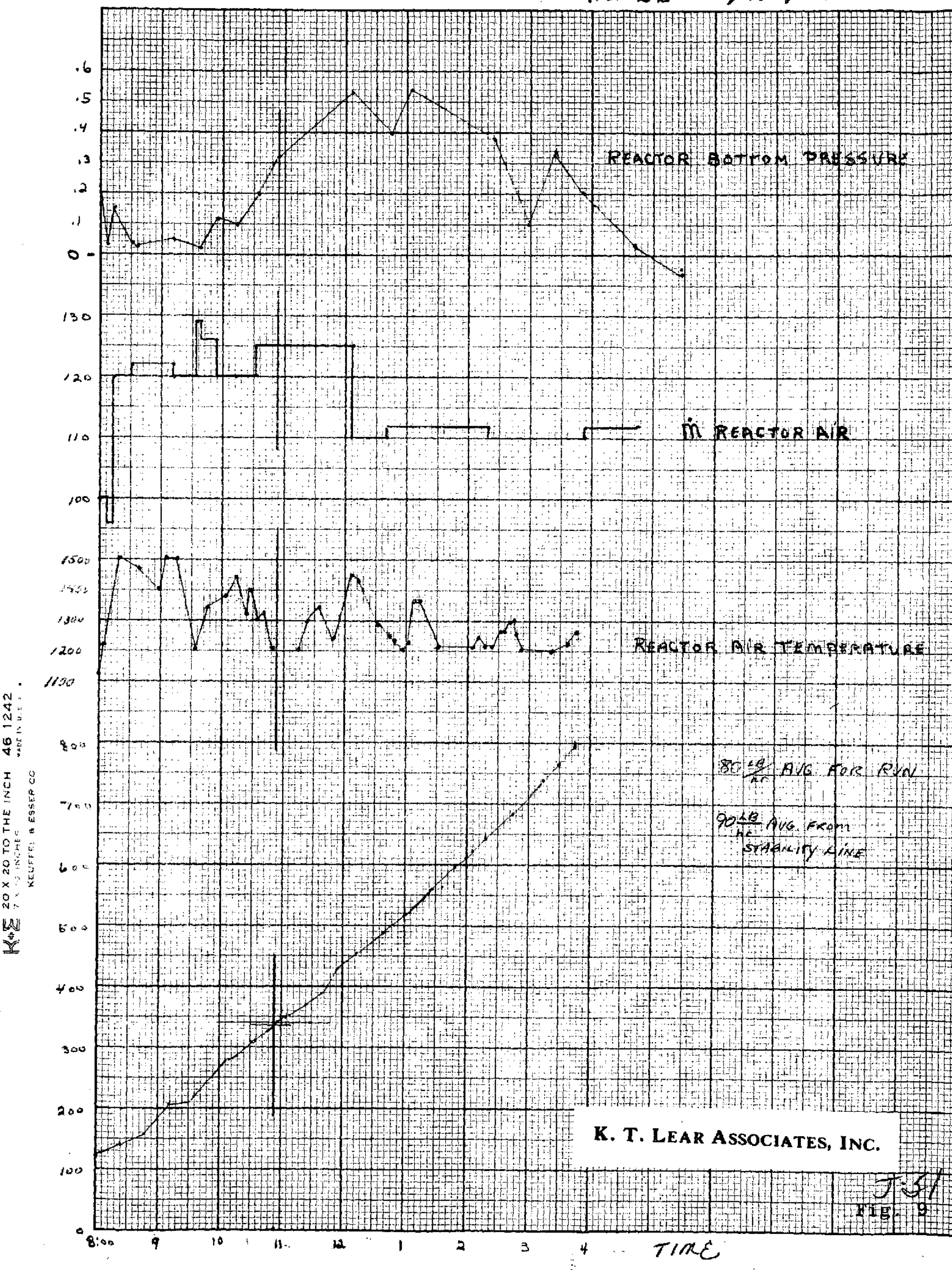


Fig. 8

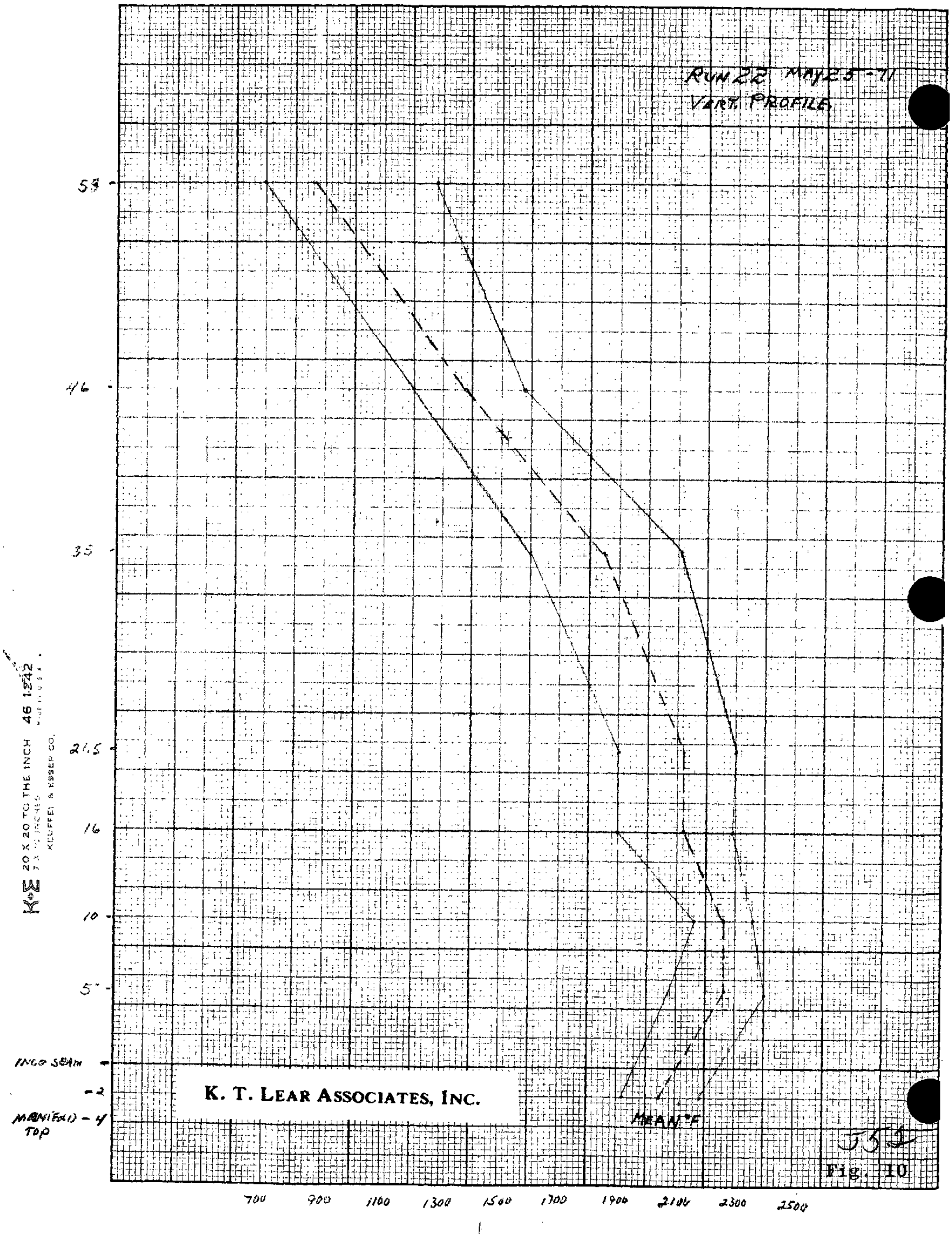
K&E 20 X 20 TO THE INCH 46 1242

RUN 22 MAY 25, 1971



K. T. LEAR ASSOCIATES, INC.

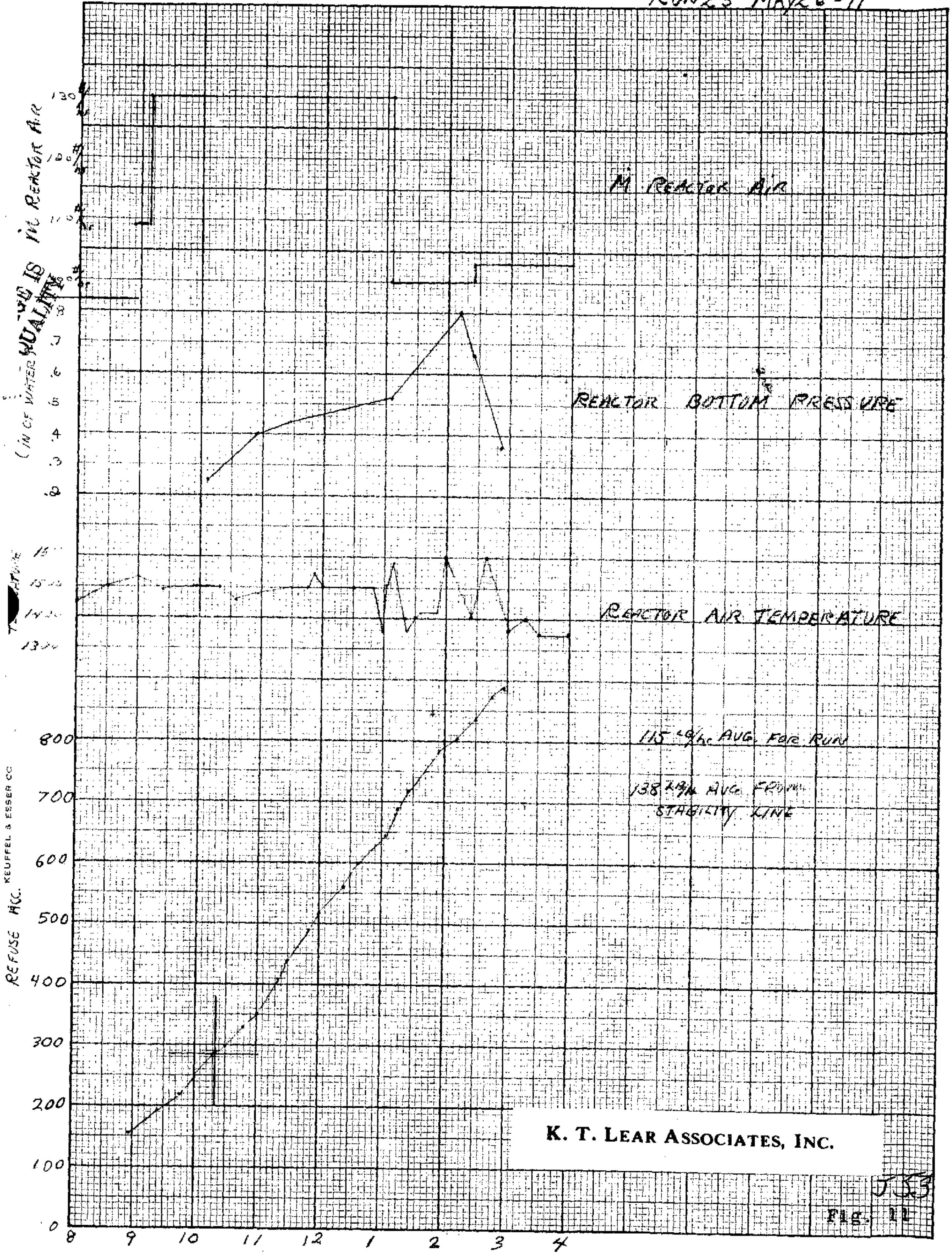
J-51
Fig. 9



RUN 22 MAY 25-71
VERT. PROFILE
53
46
35
21.5
16
10
5"
INCO SEAM
-2
MANIFOLD - 4
TOP
K. T. LEAR ASSOCIATES, INC.
MEAN °F
700
900
1100
1300
1500
1700
1900
2100
2300
2500
K+E 20 X 20 TO THE INCH 46 1242
KEUFFEL & ESSER CO.

Fig. 10

RUN 23 MAY 26-71

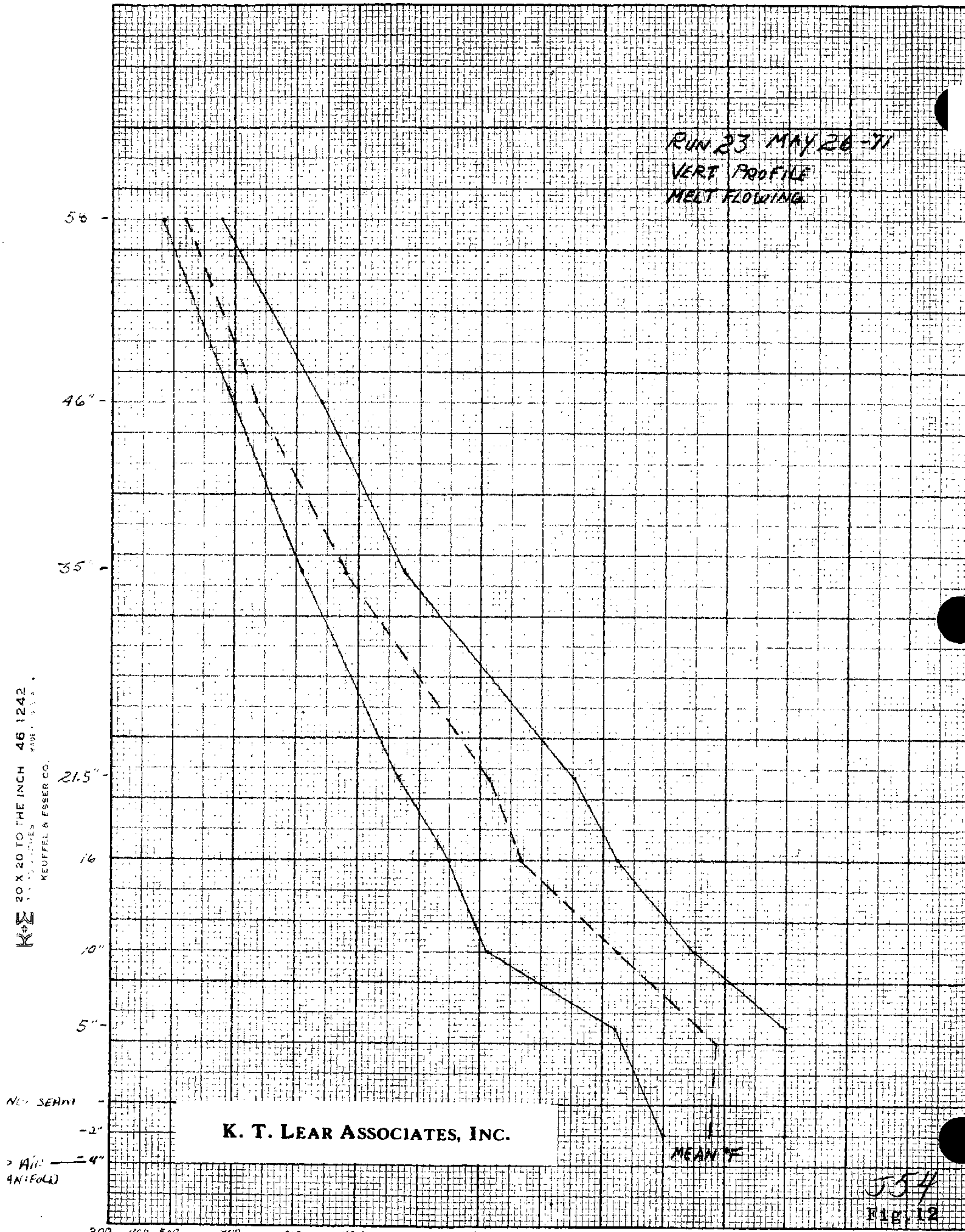


20 X 20 TO THE INCH 46 1242
7 X 10 INCHES
KEUFFEL & ESSER CO.

K. T. LEAR ASSOCIATES, INC.

J 33

Fig. 11

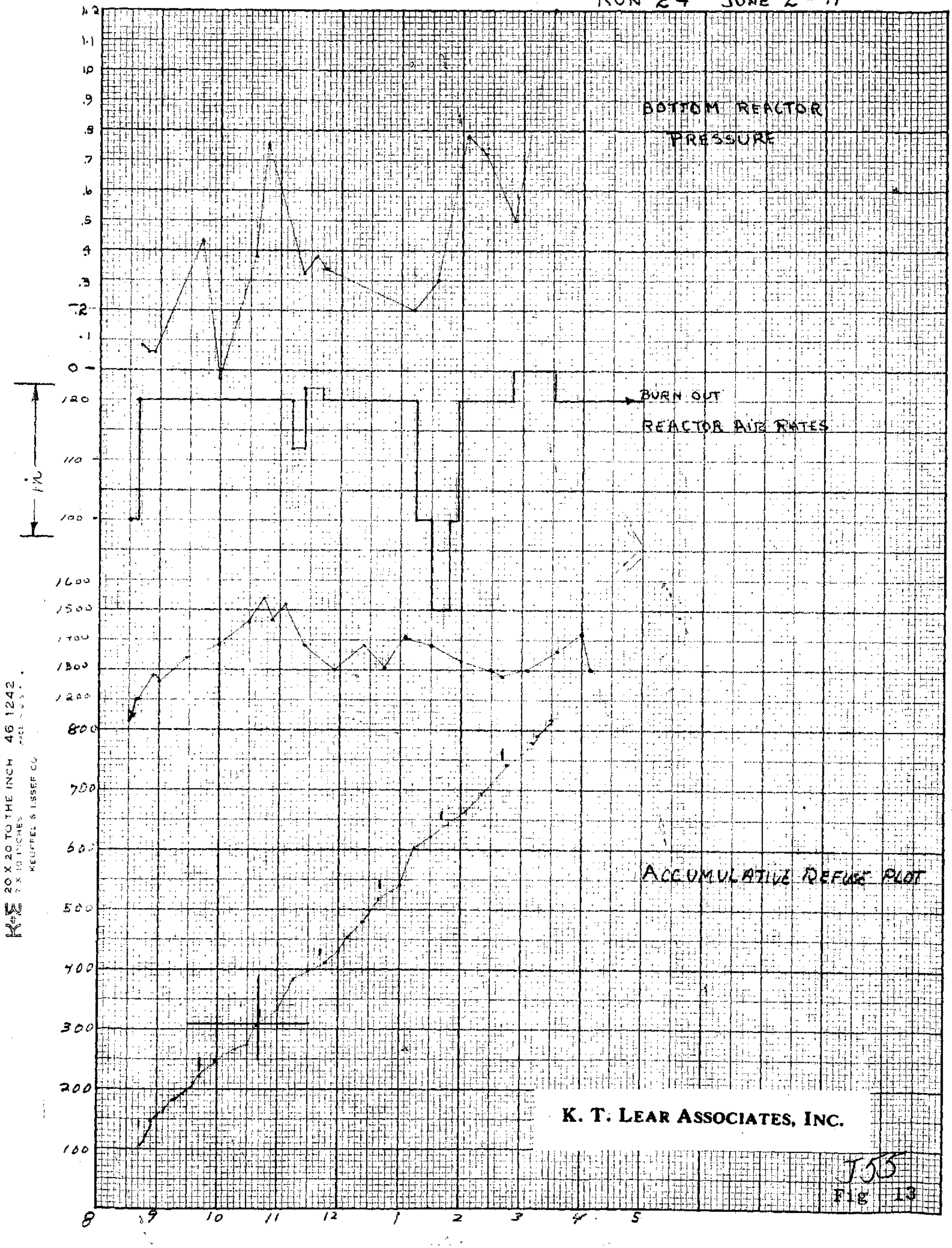


K. T. LEAR ASSOCIATES, INC.

J54

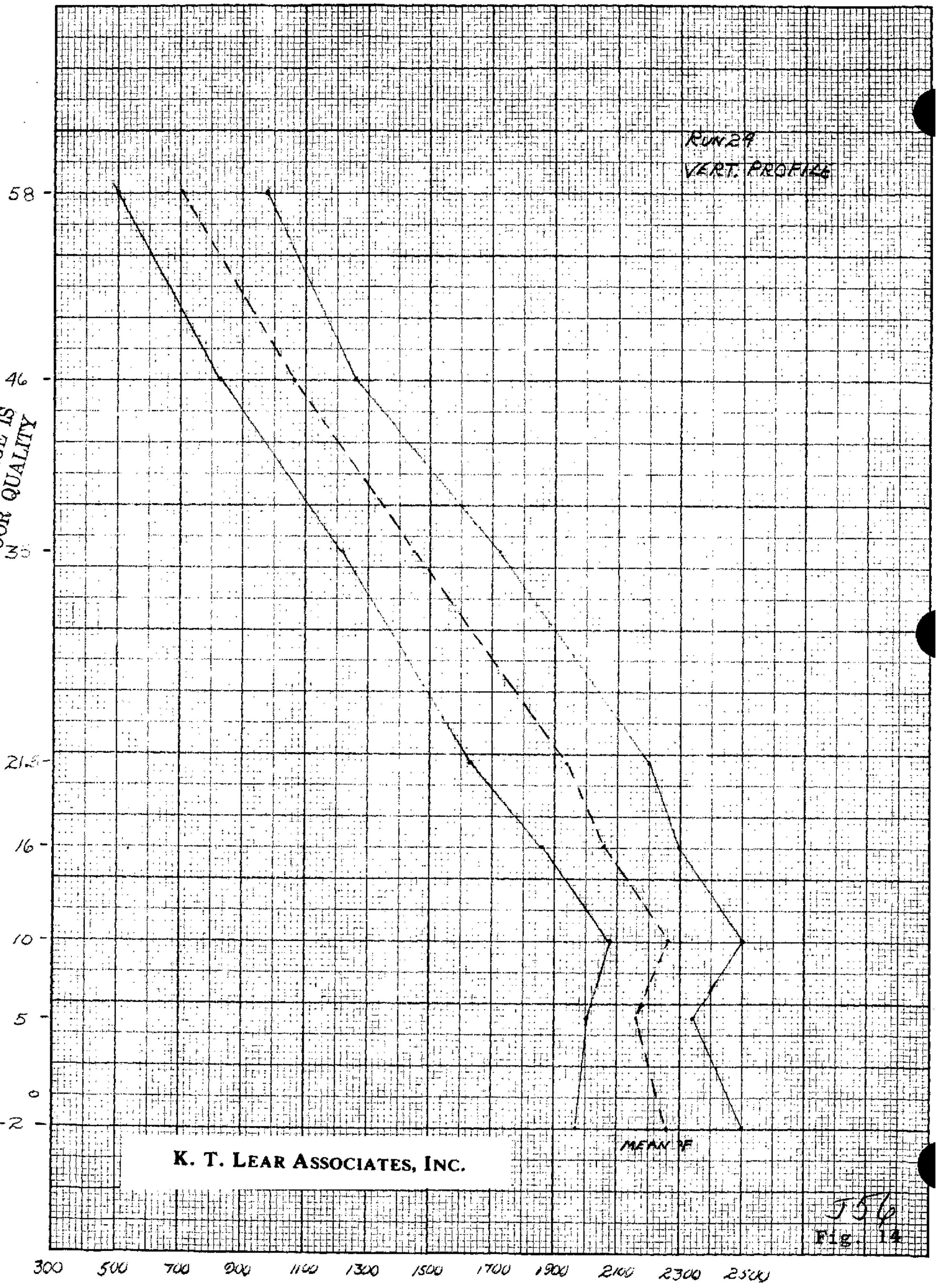
Fig. 12

RUN 24 JUNE 2-71



J55

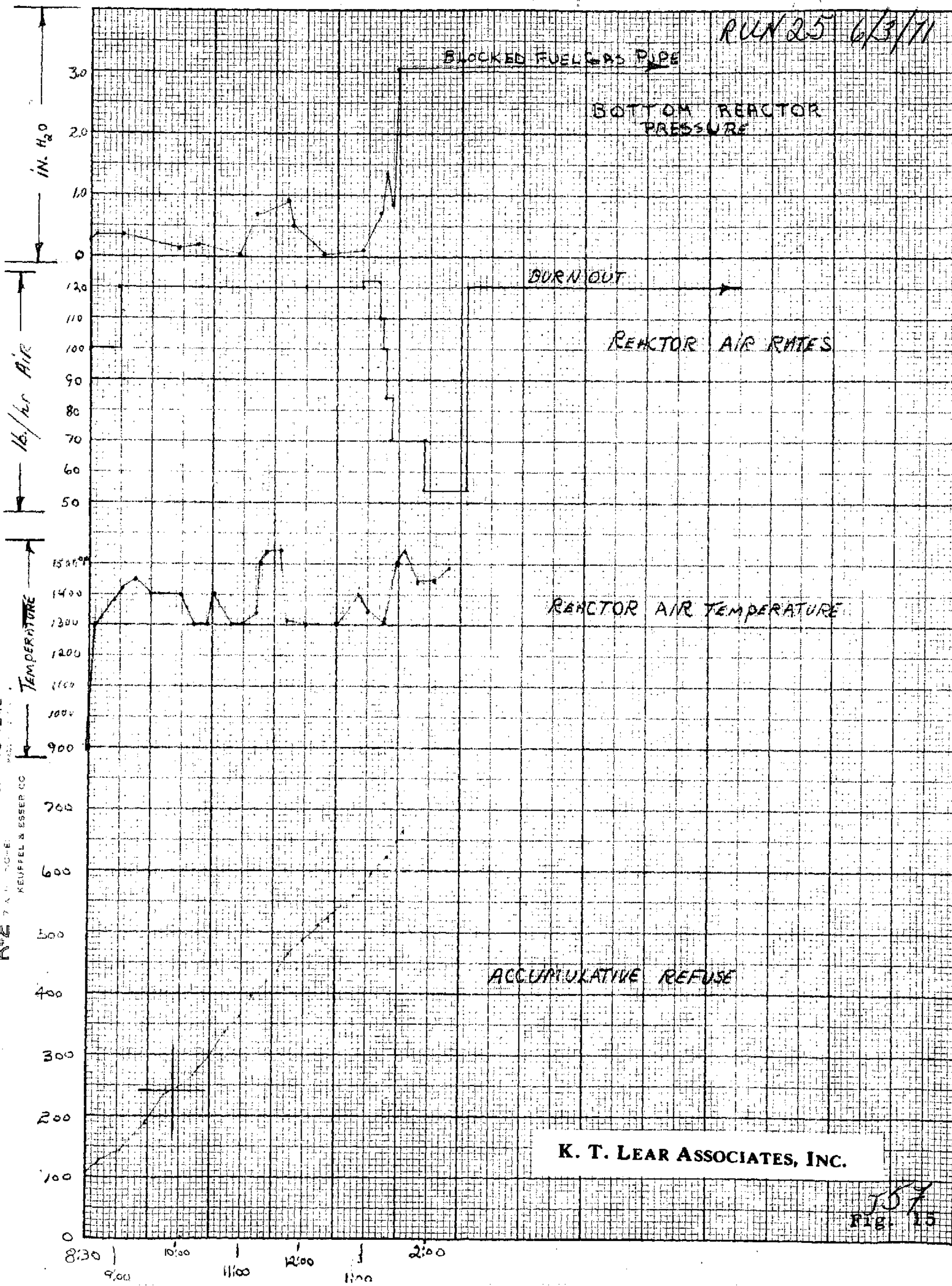
Fig 13



K. T. LEAR ASSOCIATES, INC.

J56

Fig. 14



K. T. LEAR ASSOCIATES, INC.

157

Fig. 15

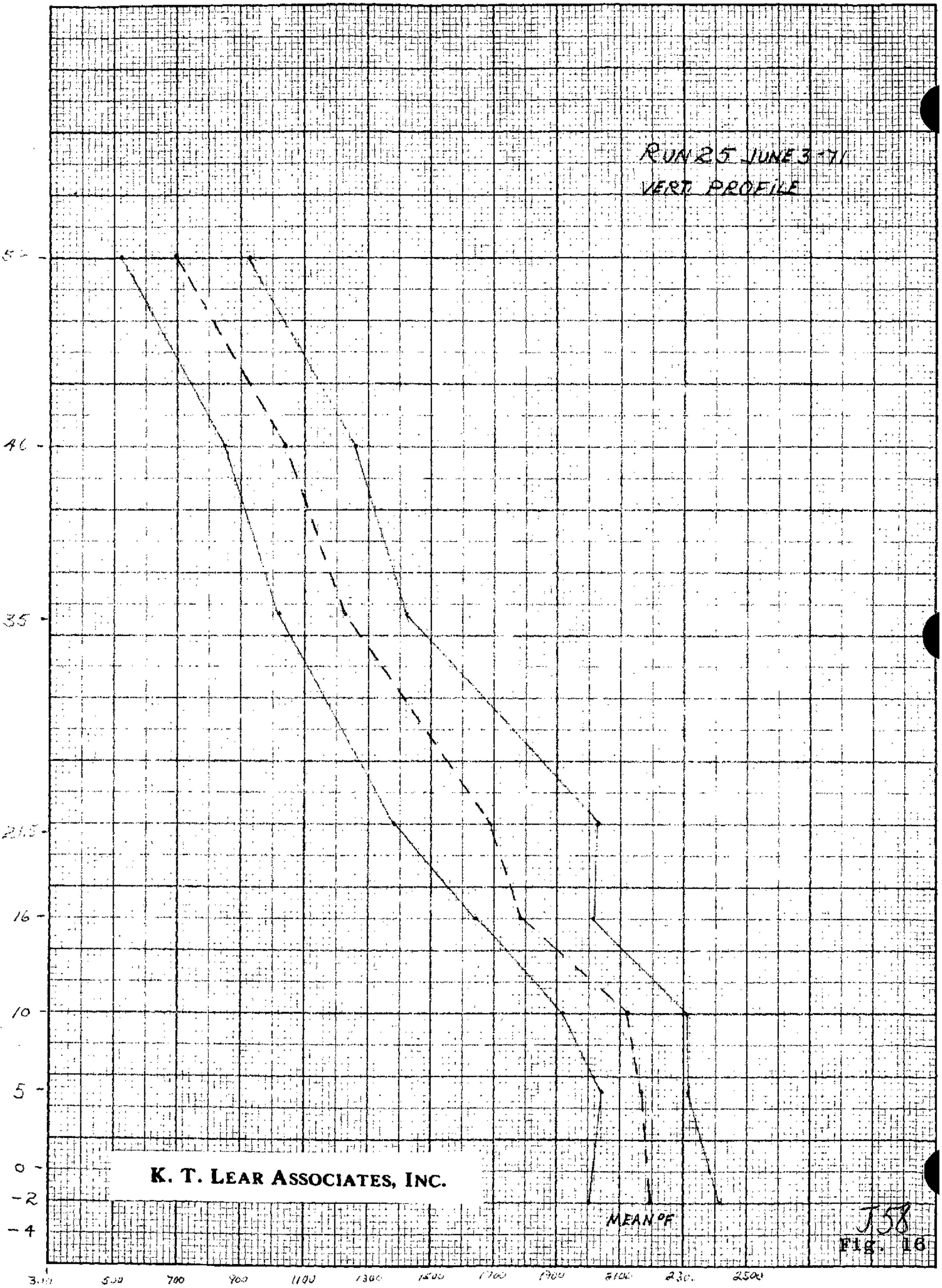
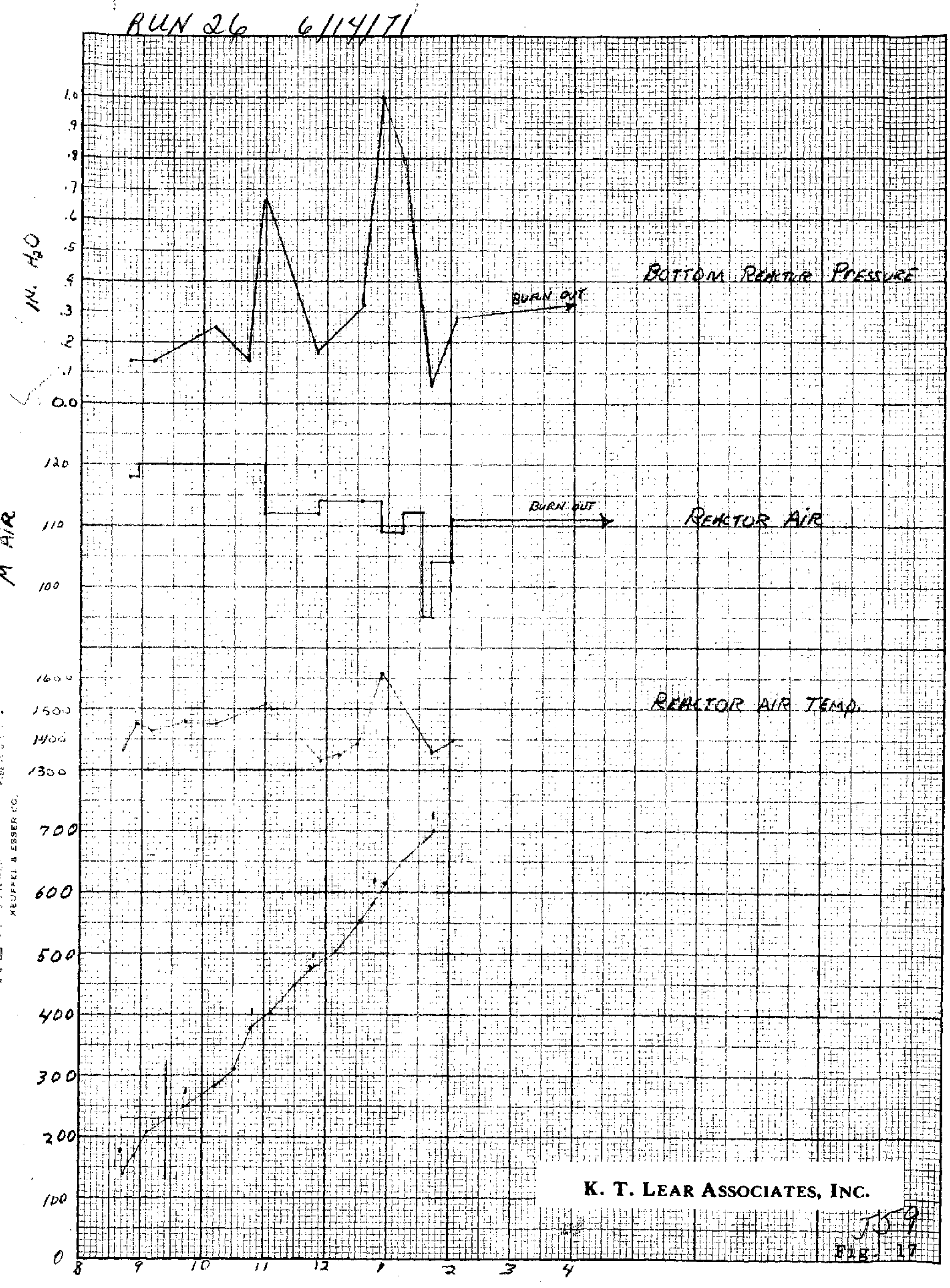

RUN 25 JUNE 3 '71
VERT. PROFILE
40
35
16
10
5
0
-2
-4
700
900
1100
1300
1500
1700
1900
2100
2500
MEAN °F
K. T. LEAR ASSOCIATES, INC.

Fig. 16

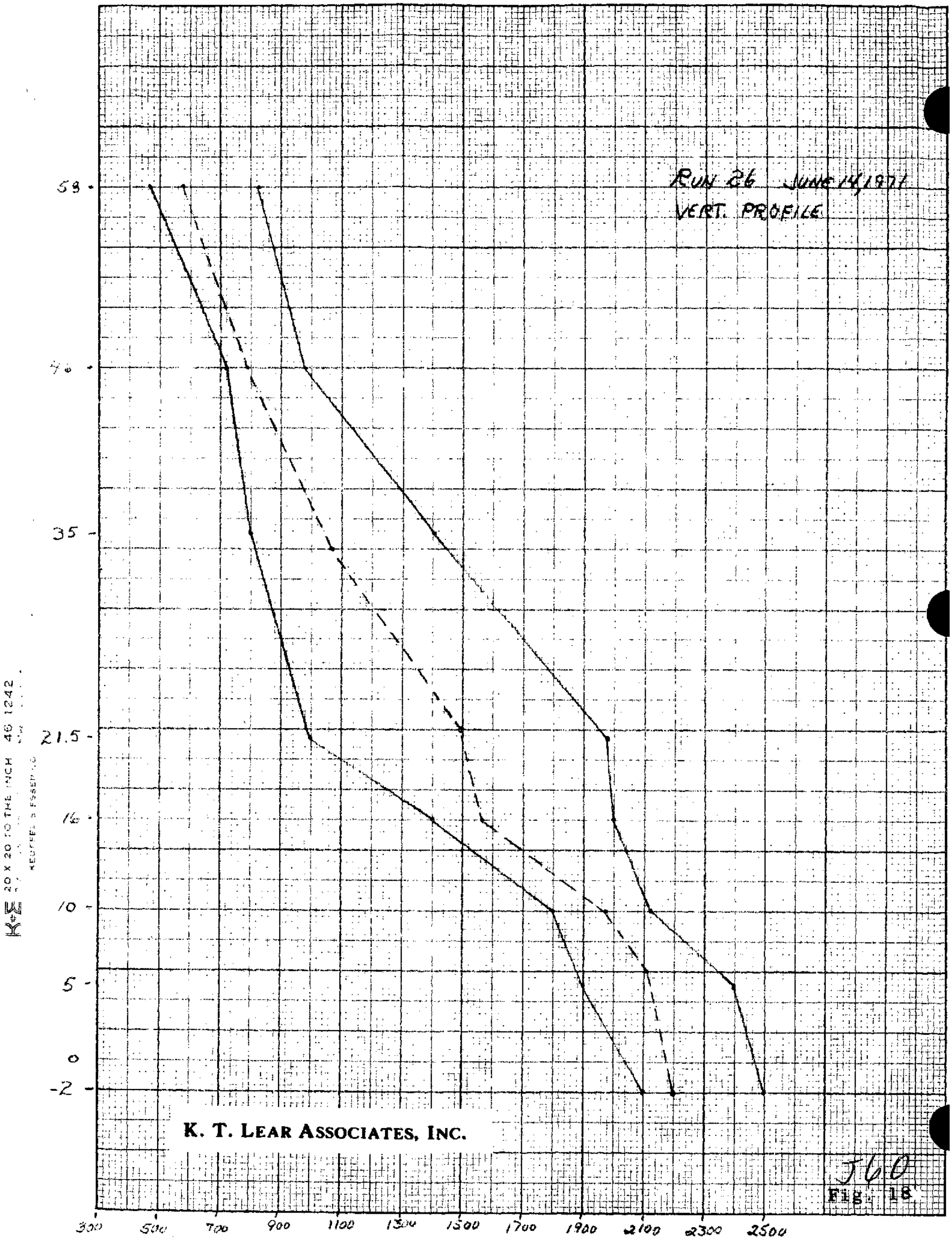
J58



K. T. LEAR ASSOCIATES, INC.

JT 9

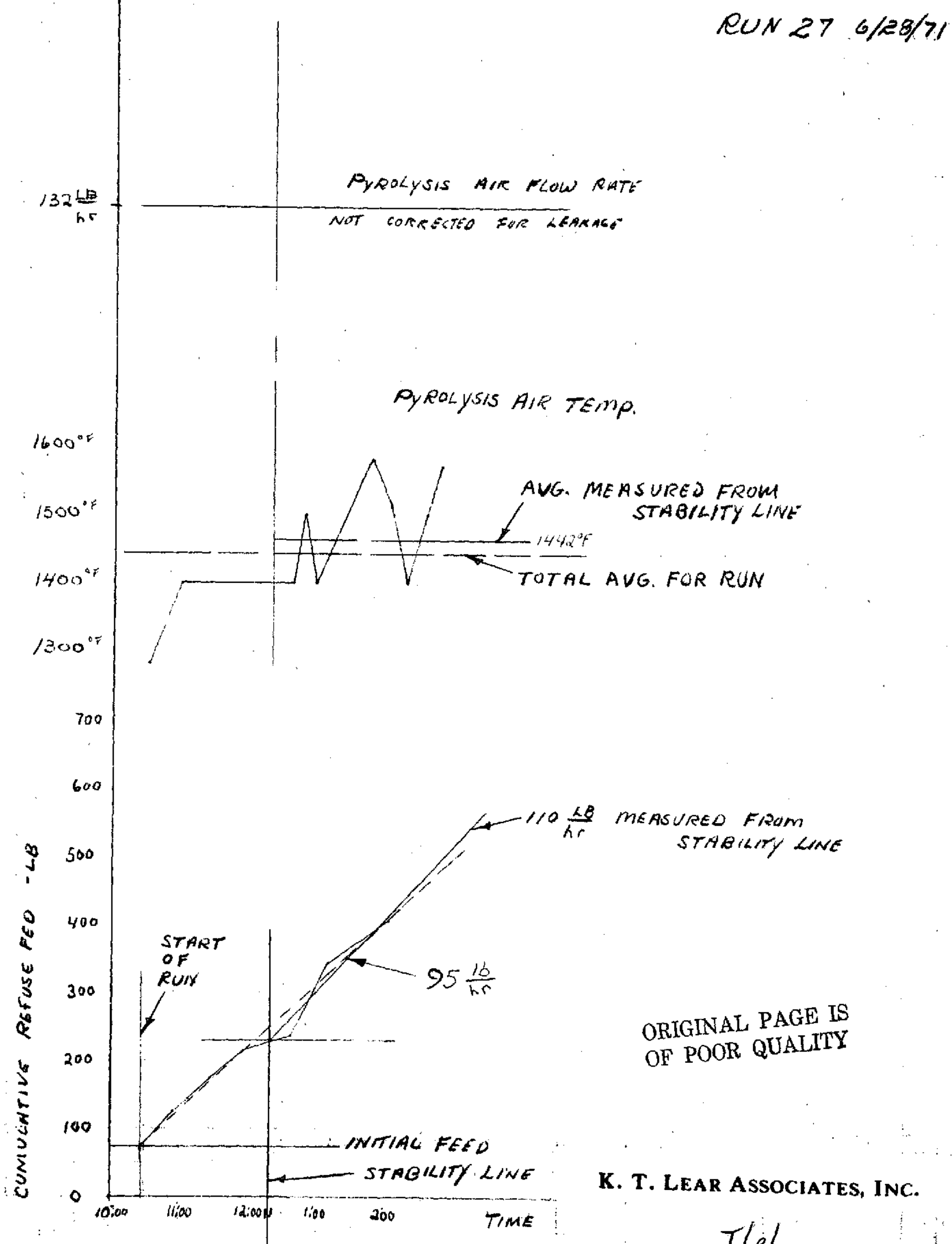
Fig. 17



K. T. LEAR ASSOCIATES, INC.

J60

Fig. 18



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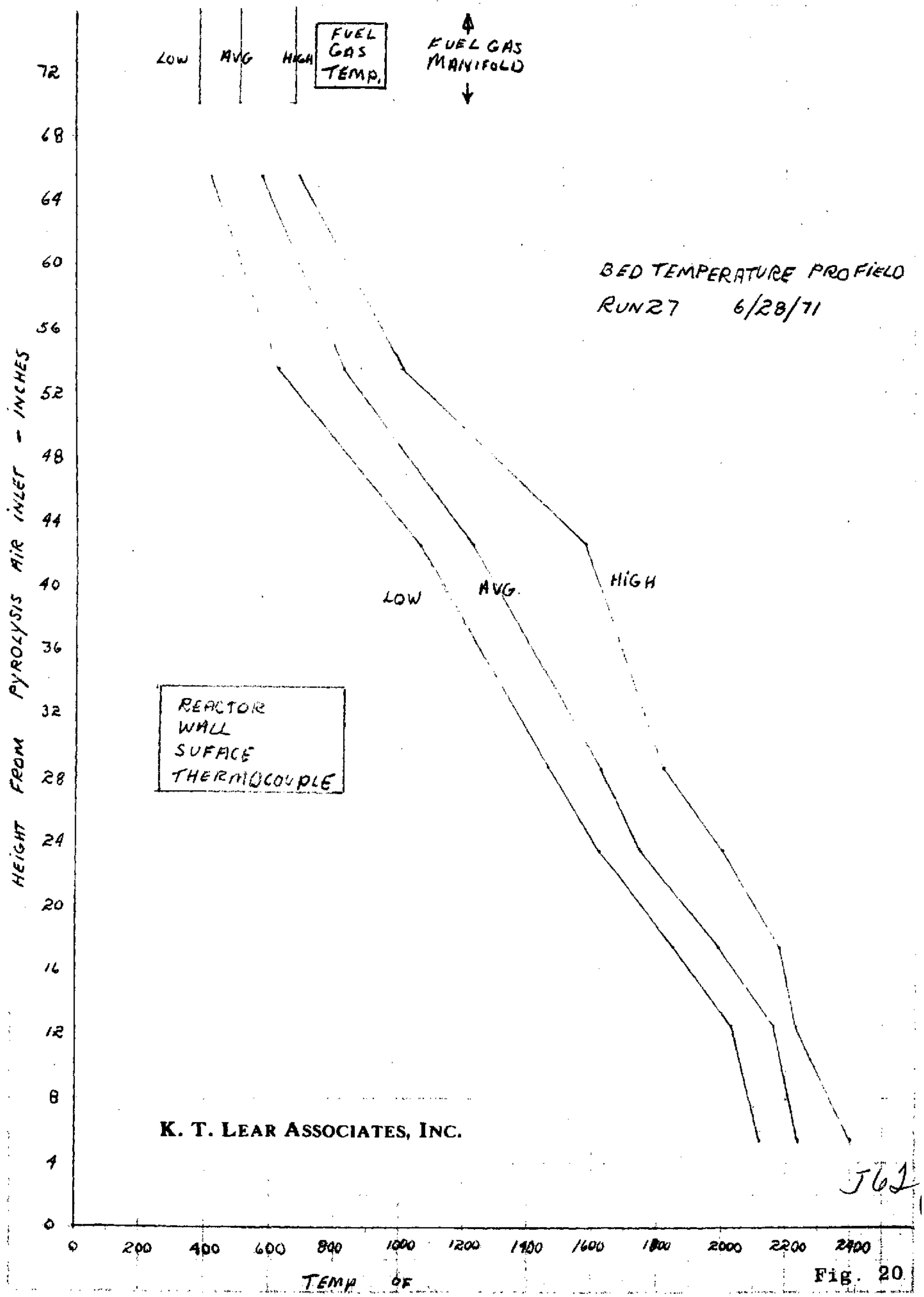
J61

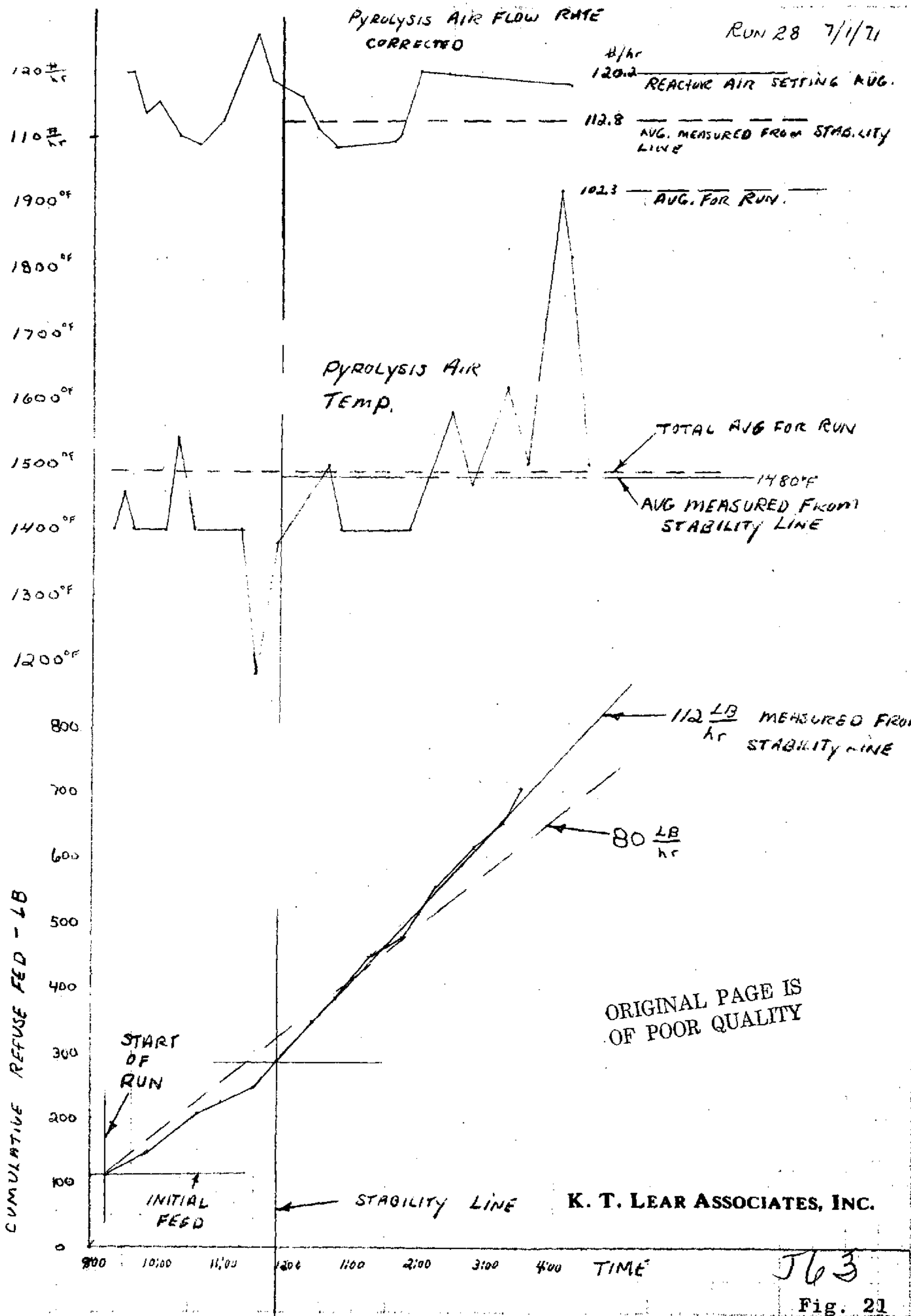
Fig. 19



K. T. LEAR ASSOCIATES, INC.

J62

Fig. 20

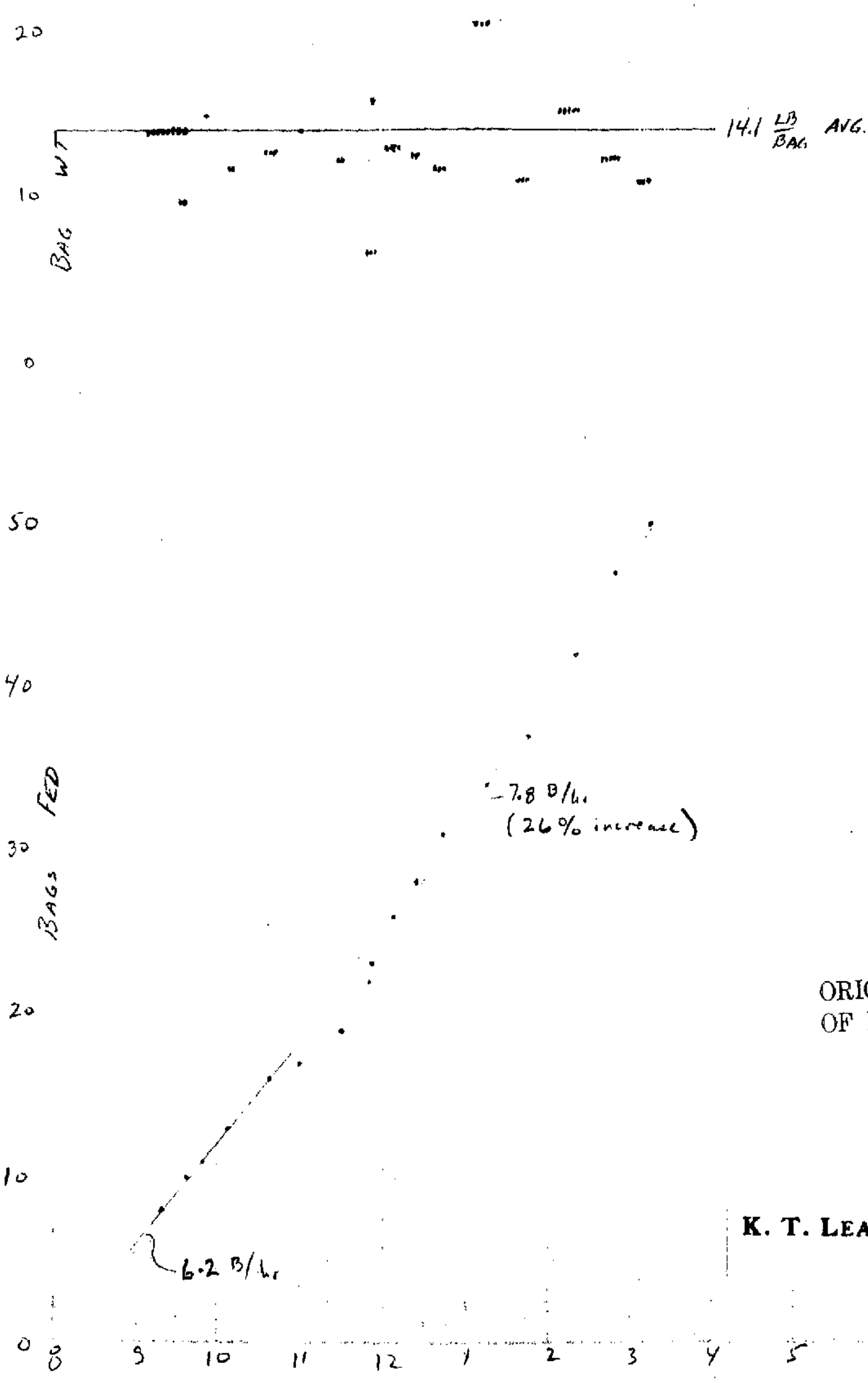


K. T. LEAR ASSOCIATES, INC.

J63

Fig. 21

Run No 28 7/1/71



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J64

Fig. 22

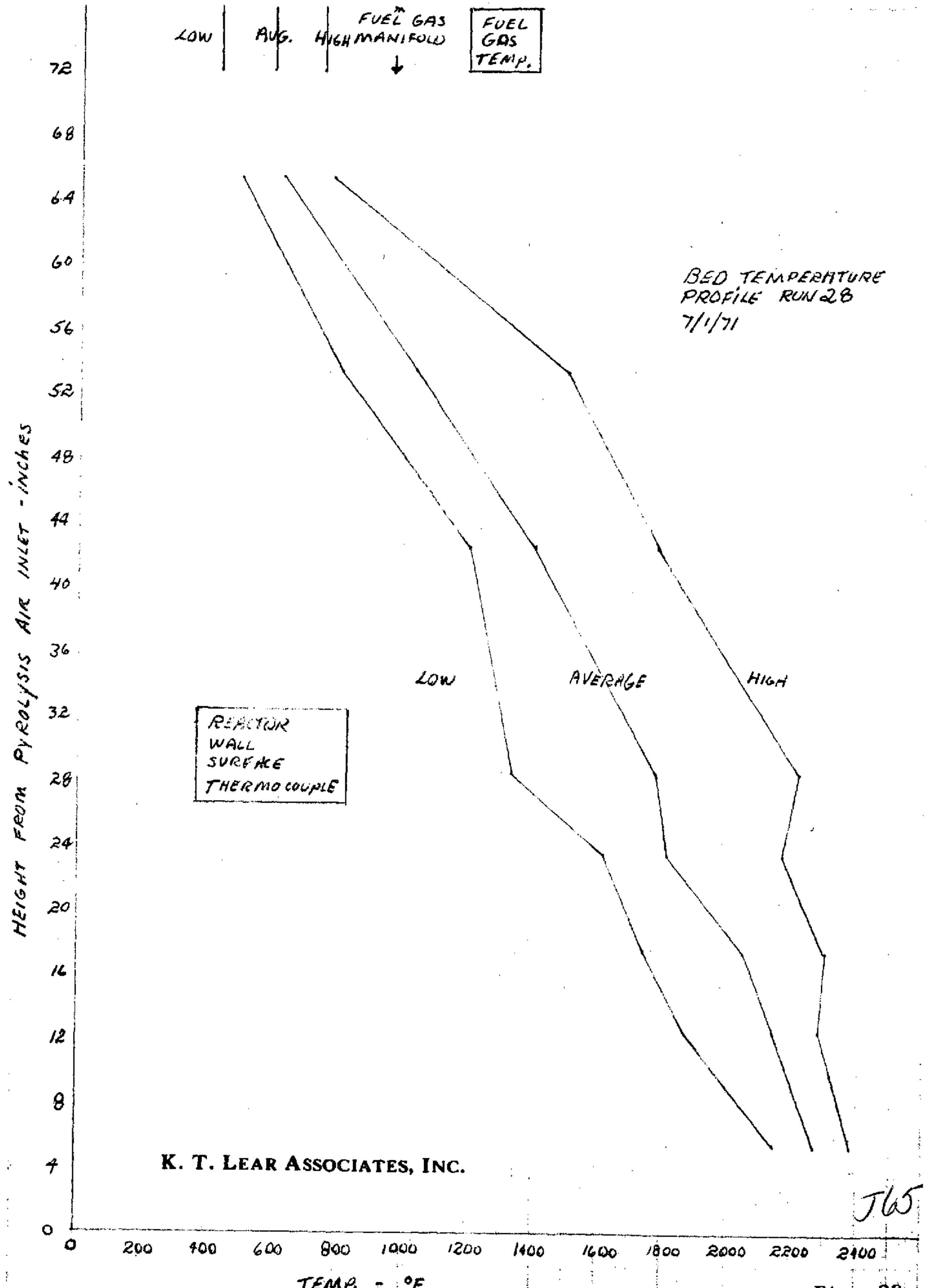

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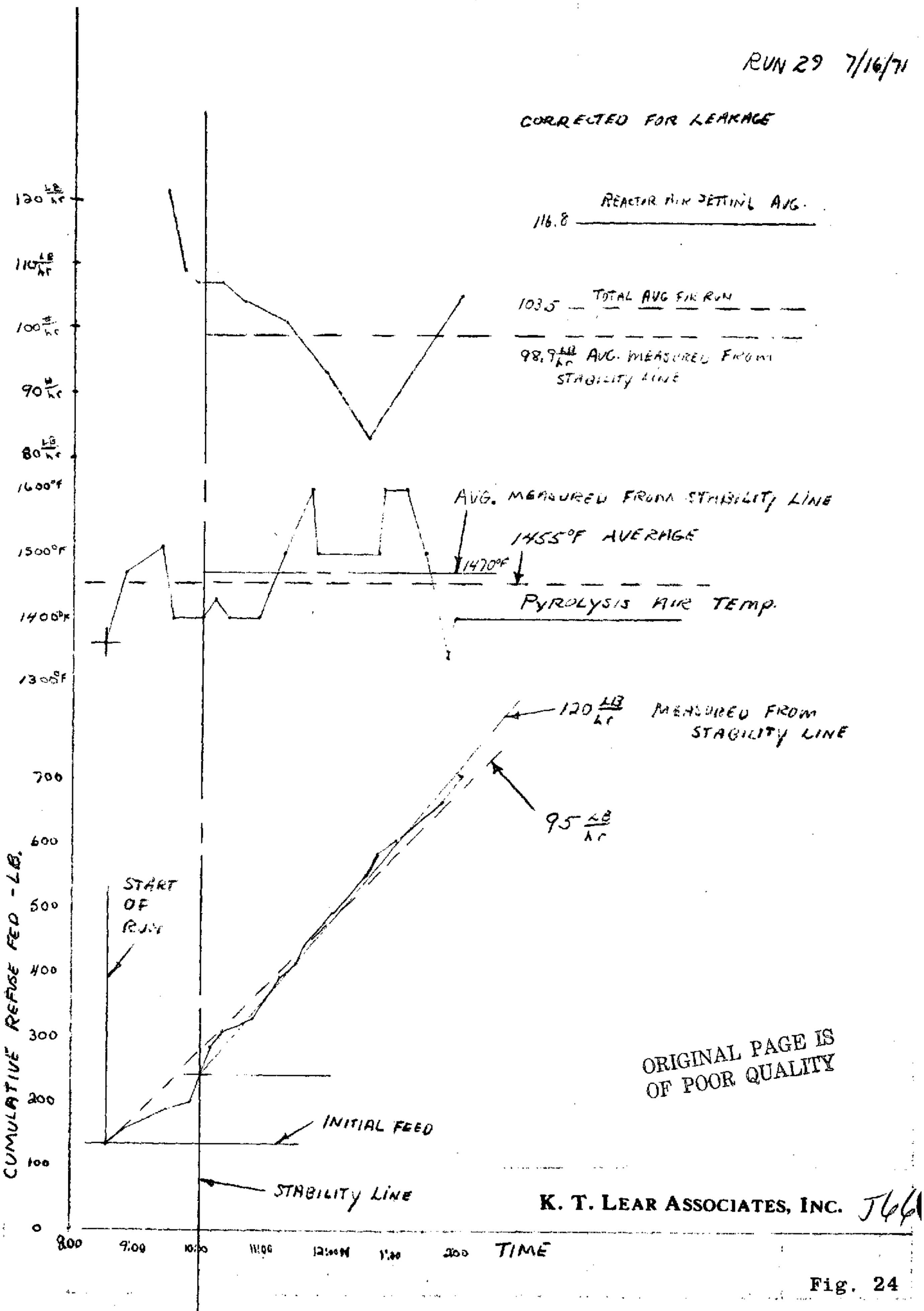
Fig. 23



K. T. LEAR ASSOCIATES, INC.

Fig. 24

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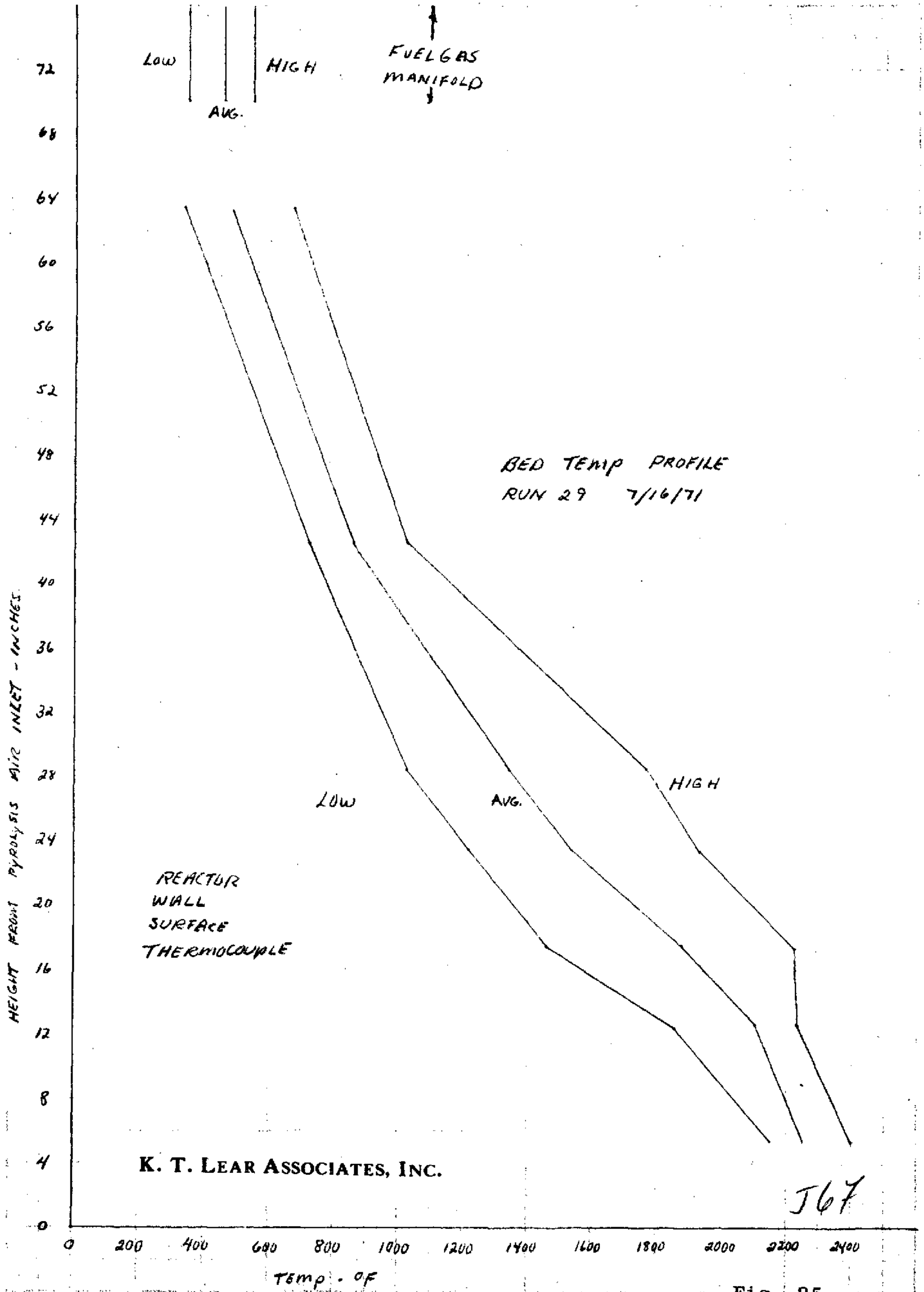
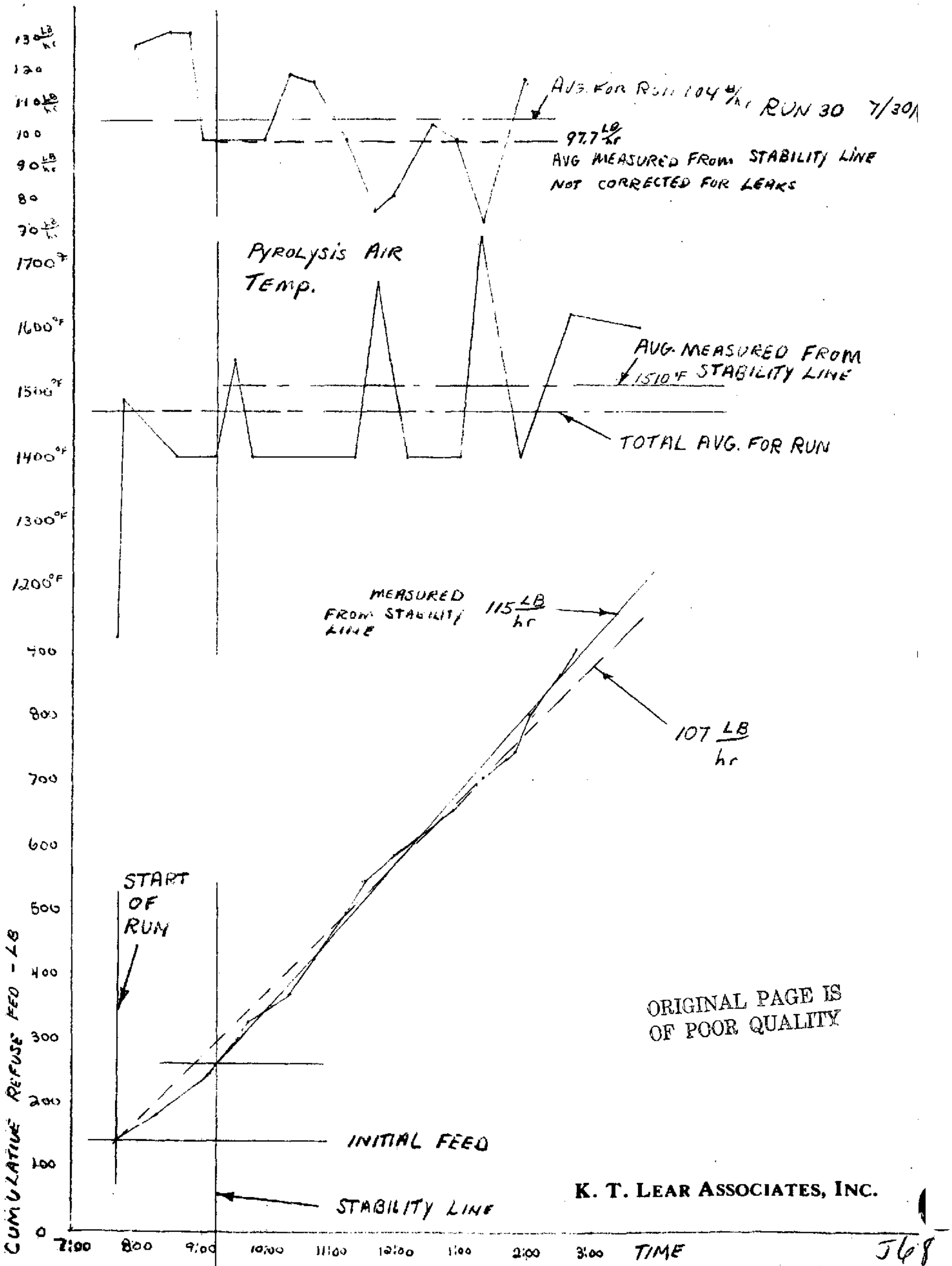


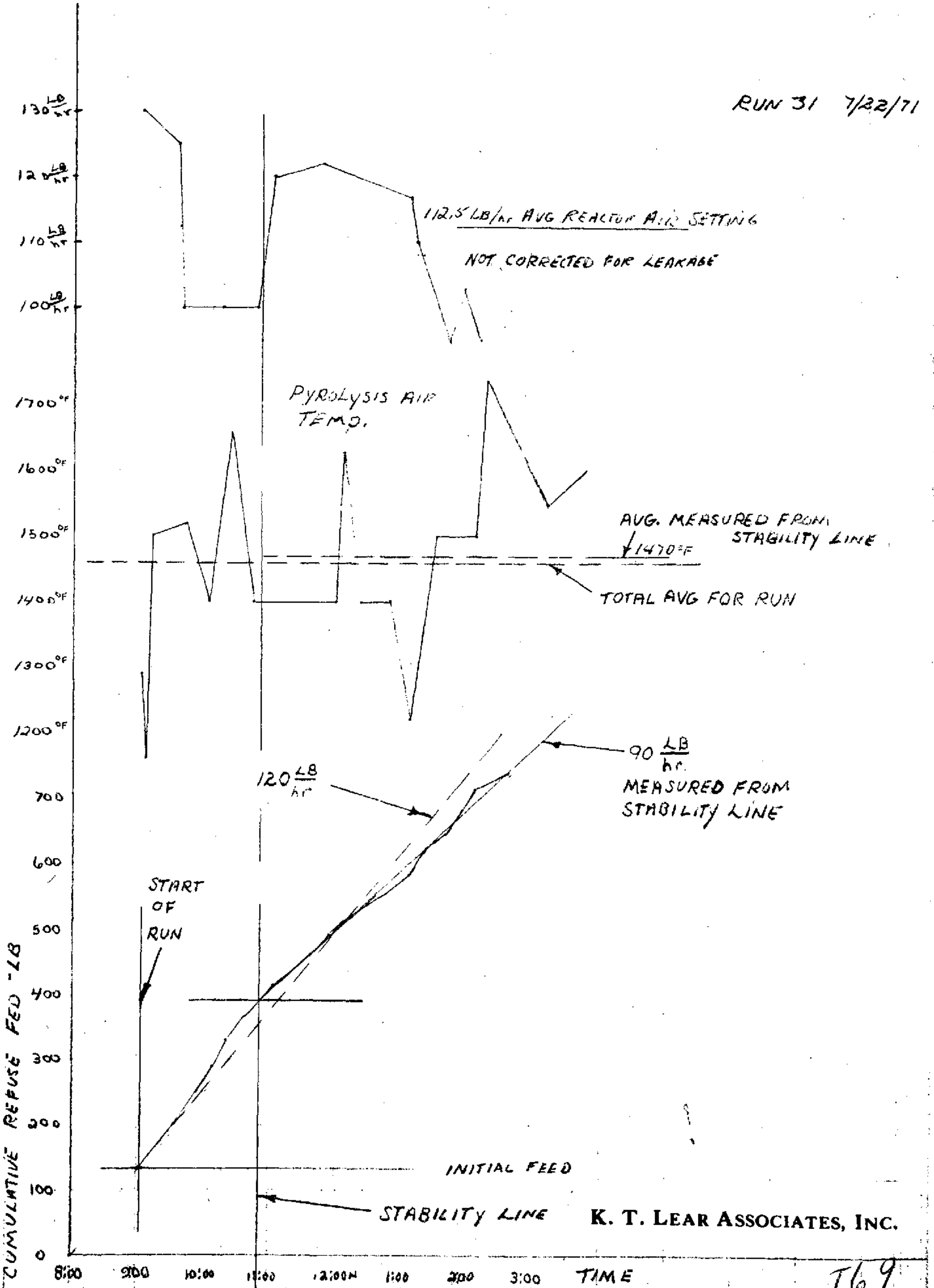
K. T. LEAR ASSOCIATES, INC.

Fig. 25



K. T. LEAR ASSOCIATES, INC.

Fig. 26



K. T. LEAR ASSOCIATES, INC.

J69

Fig. 27

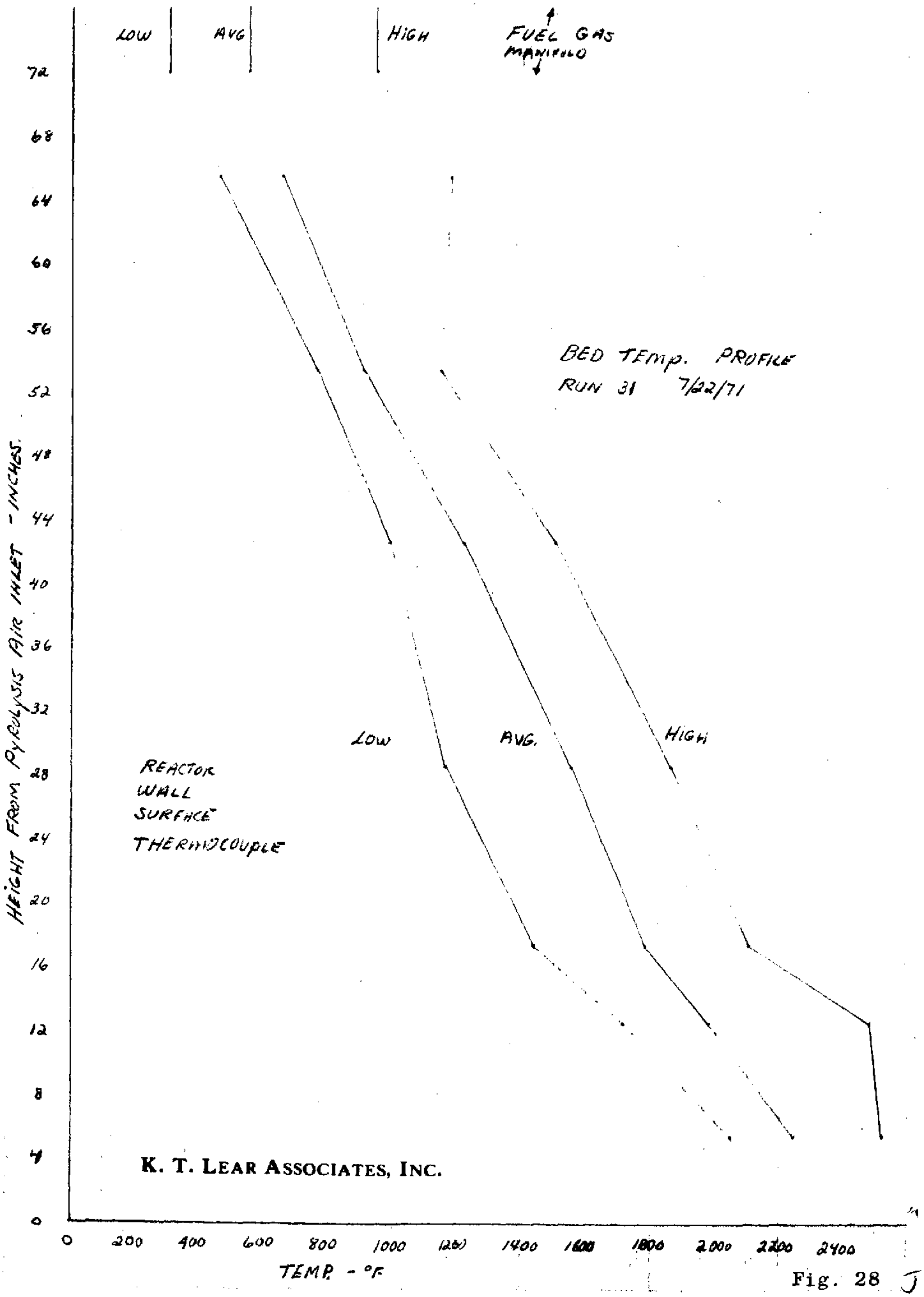
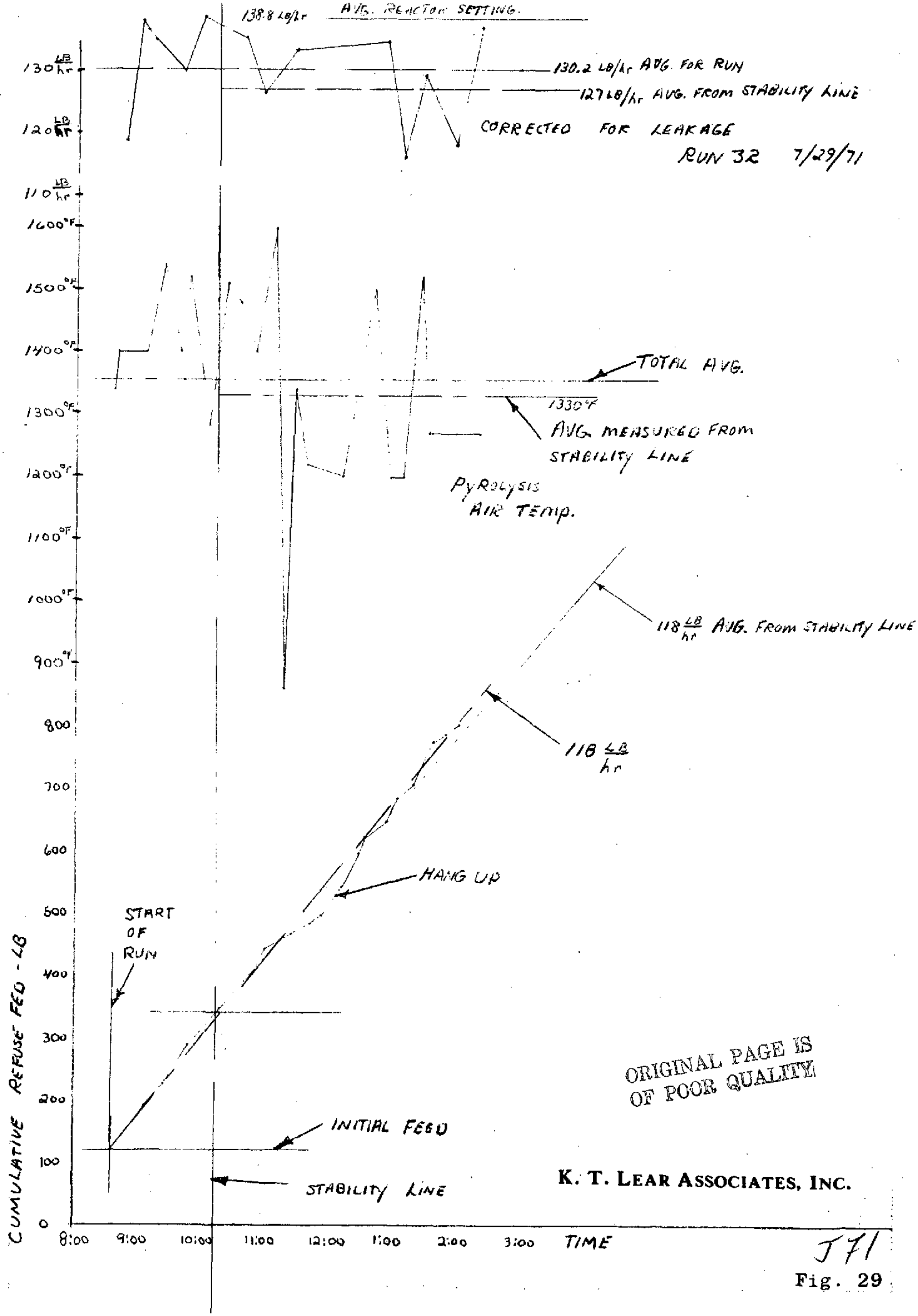

LOW
AVG
HIGH
FUEL GAS MANIFOLD
BED TEMP. PROFILE
RUN 31 7/22/71
LOW
AVG.
HIGH
REACTOR WALL SURFACE THERMOCOUPLE
HEIGHT FROM PYROLYSIS AIR INLET - INCHES
72
68
64
60
56
52
48
44
40
36
32
28
24
20
16
12
8
4
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TEMP. - °F
K. T. LEAR ASSOCIATES, INC.

Fig. 28



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J71

Fig. 29

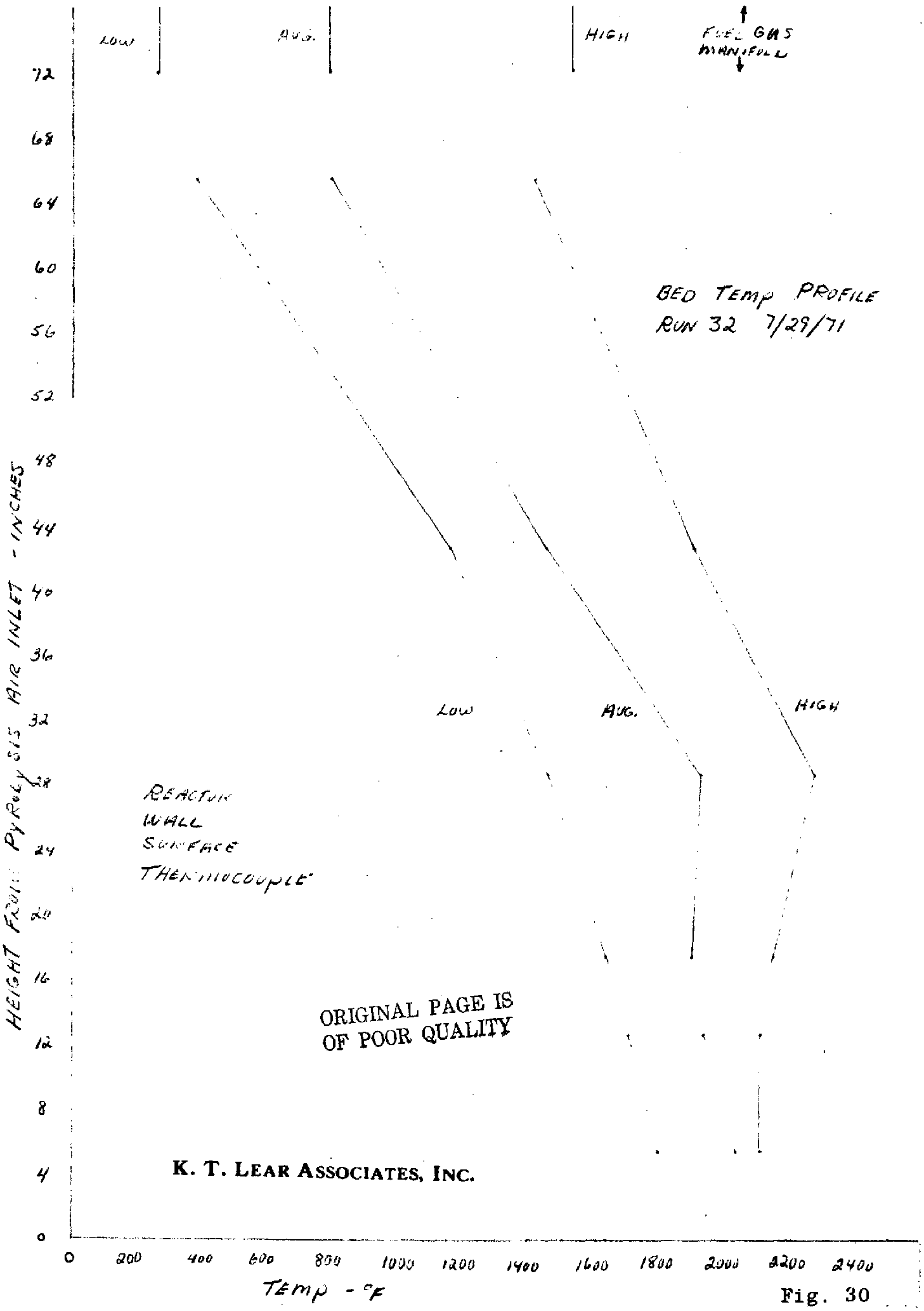

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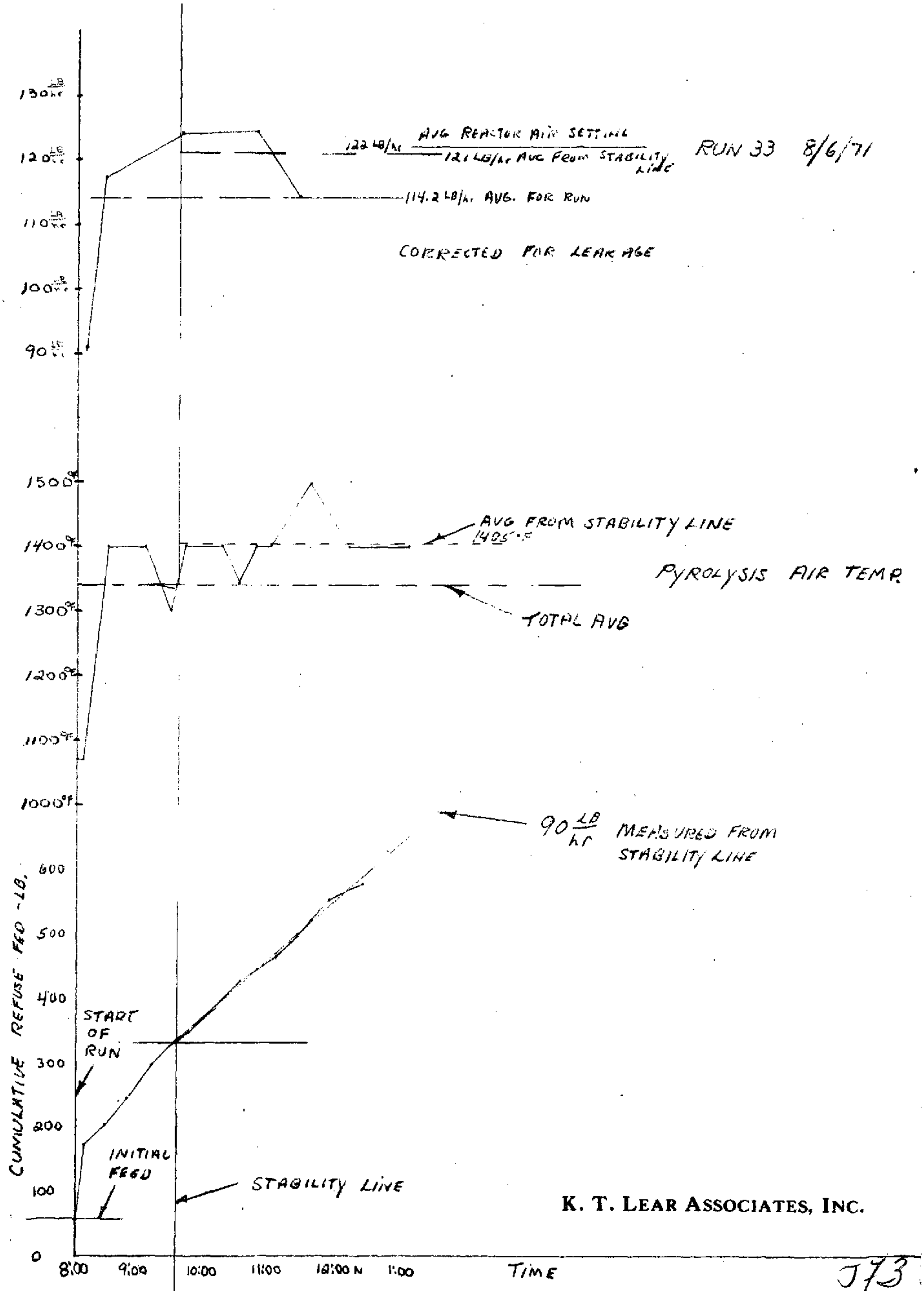
Fig. 30

J72



K. T. LEAR ASSOCIATES, INC.

Fig. 31

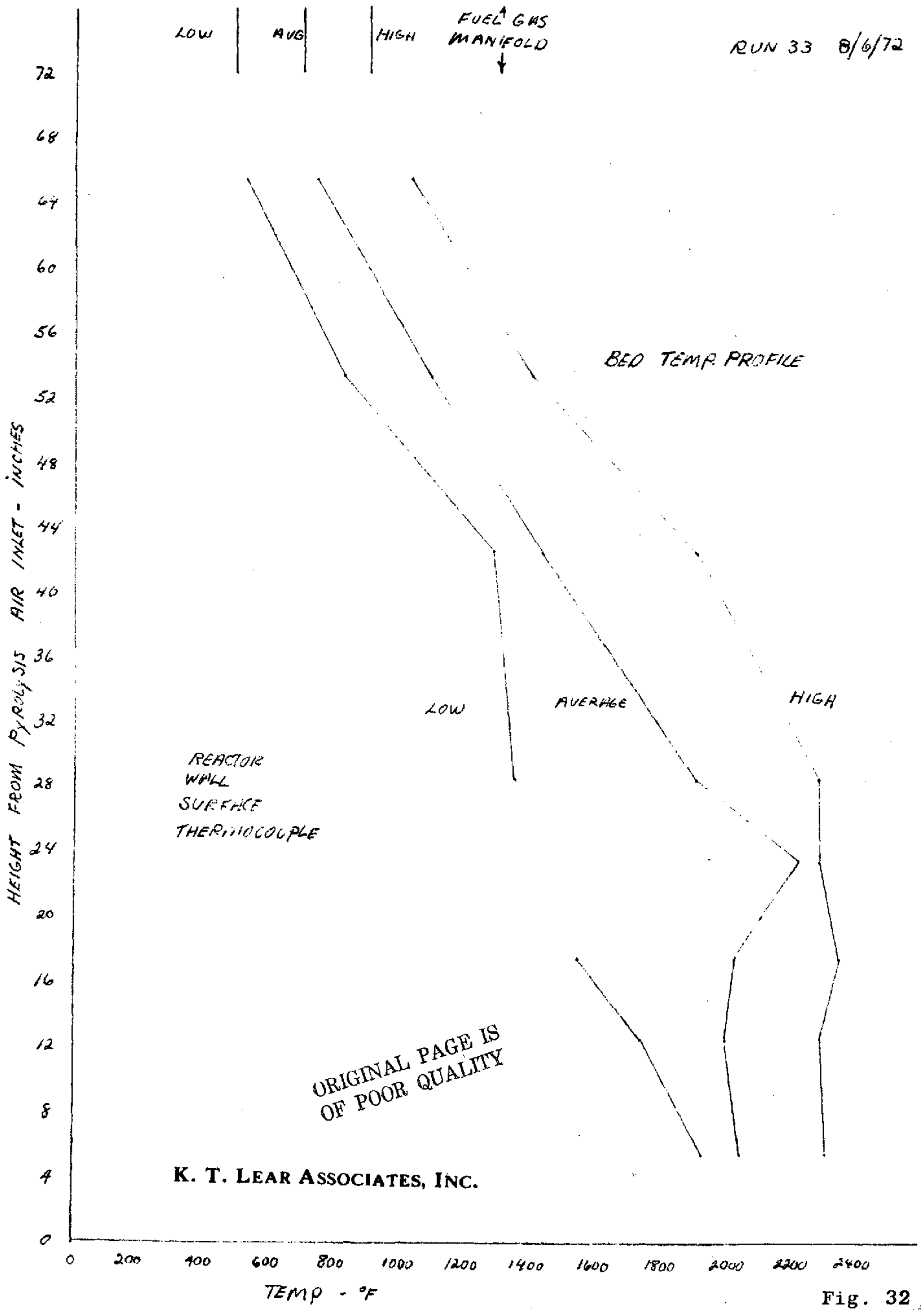


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Fig. 32

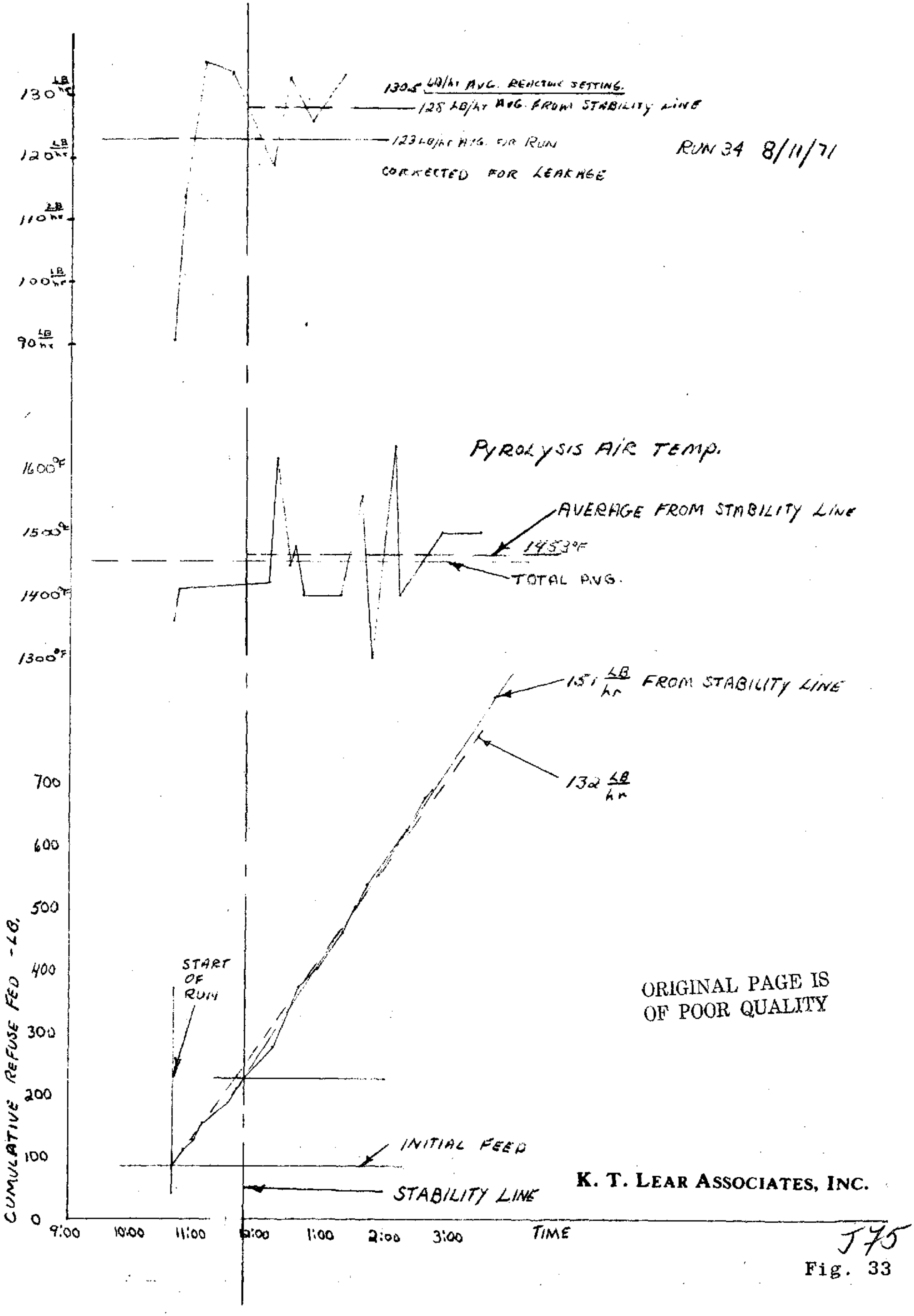

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Fig. 33

J.S.D in plot

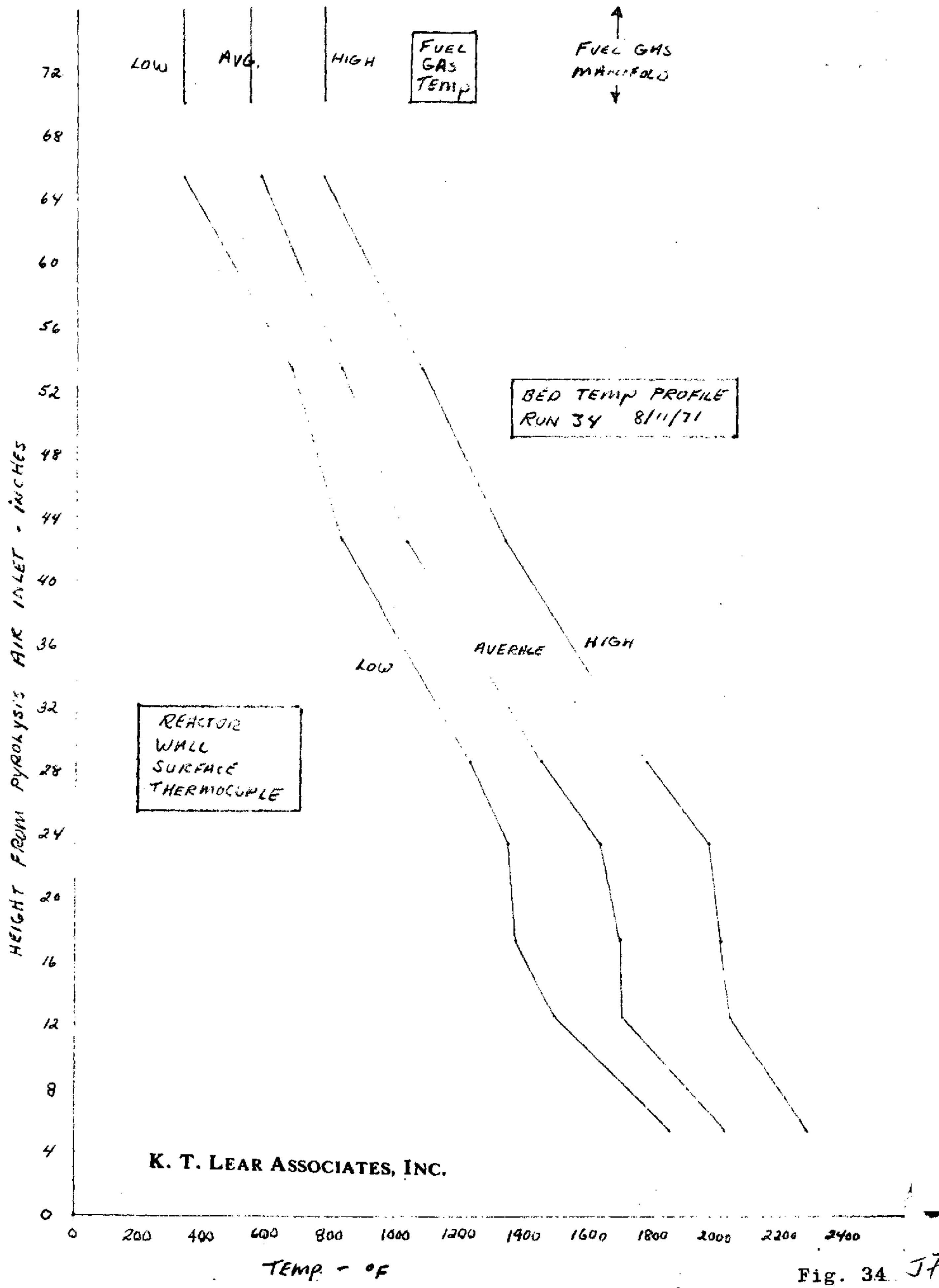
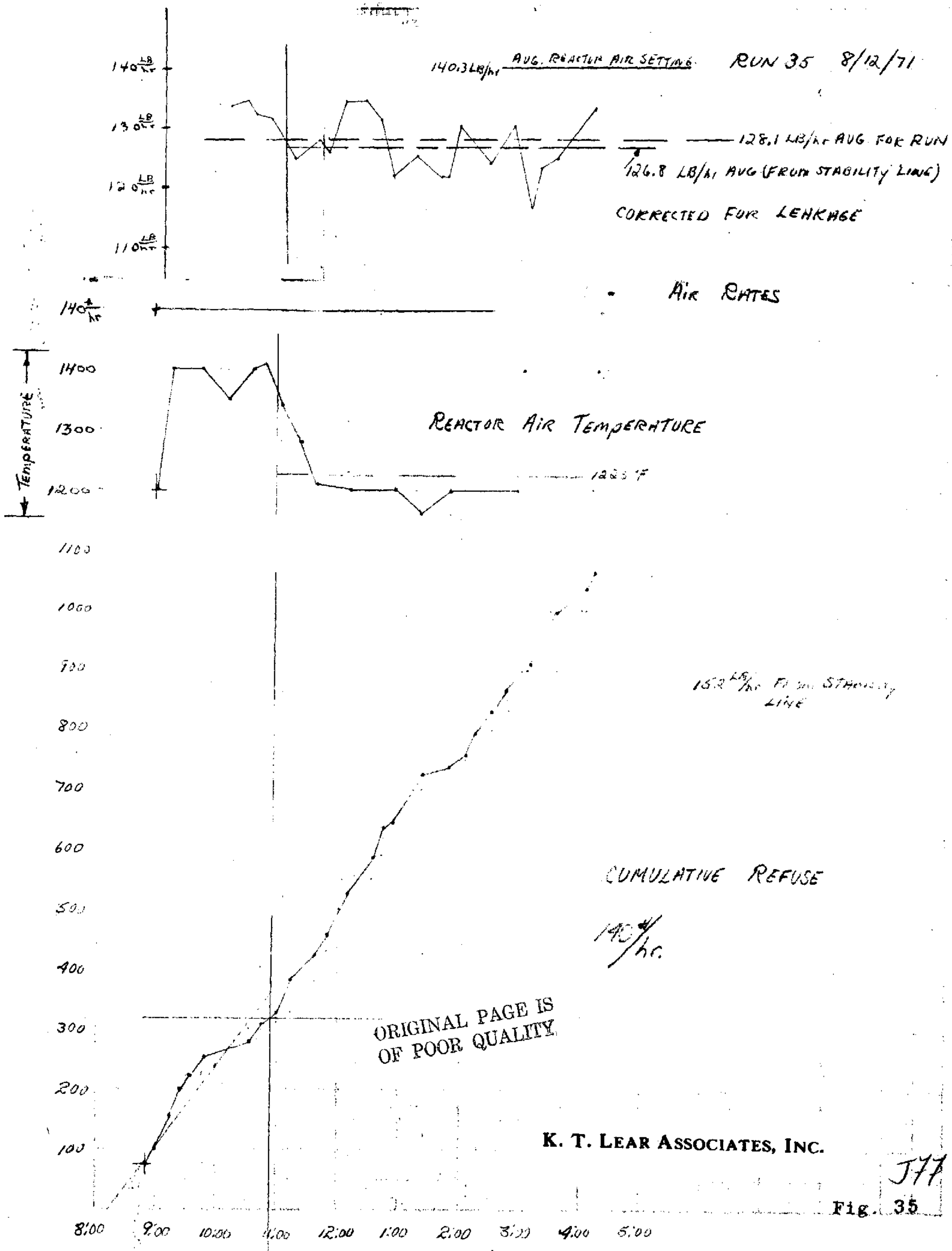


Fig. 34 J76



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J77

Fig. 35

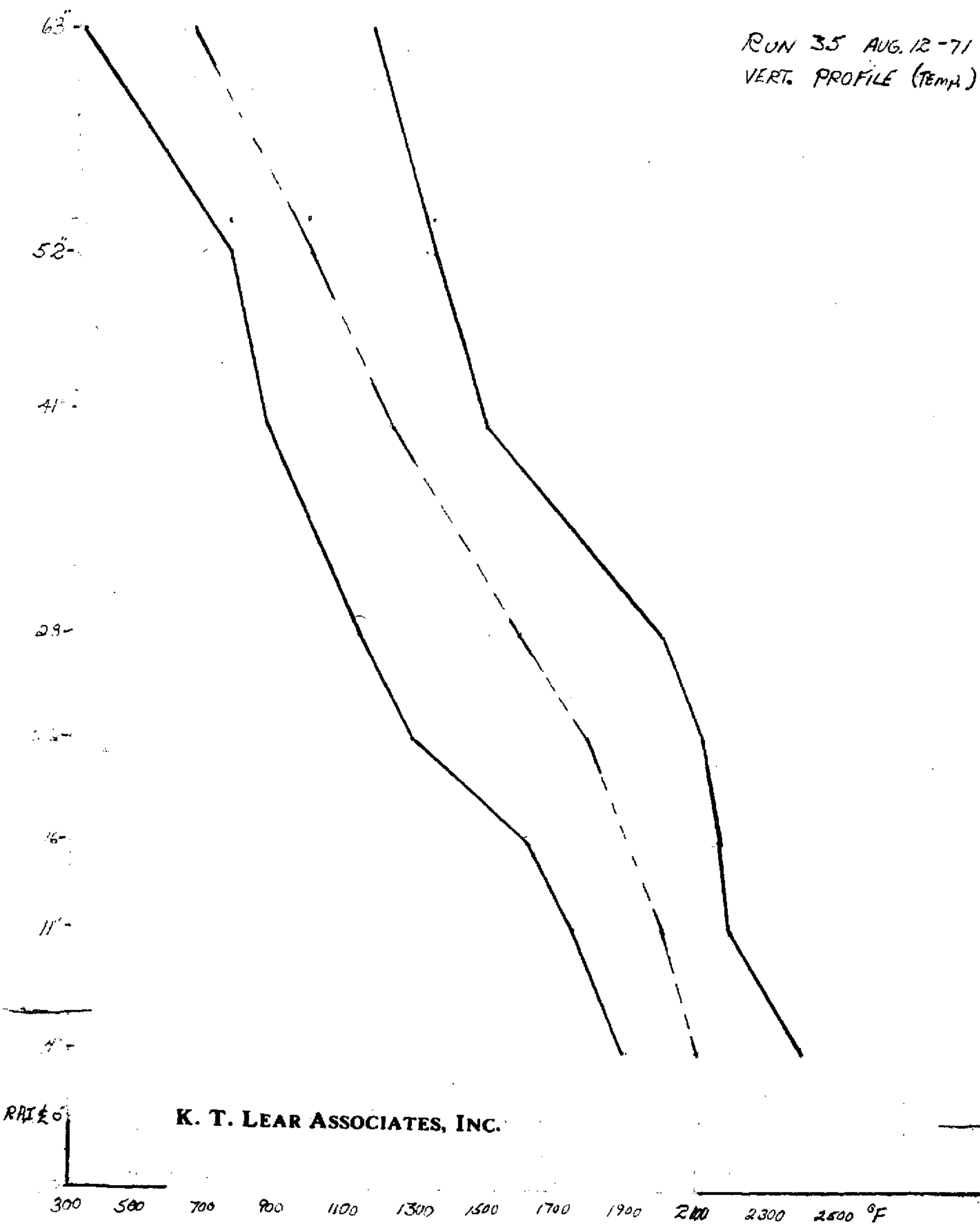

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Fig. 36

J78

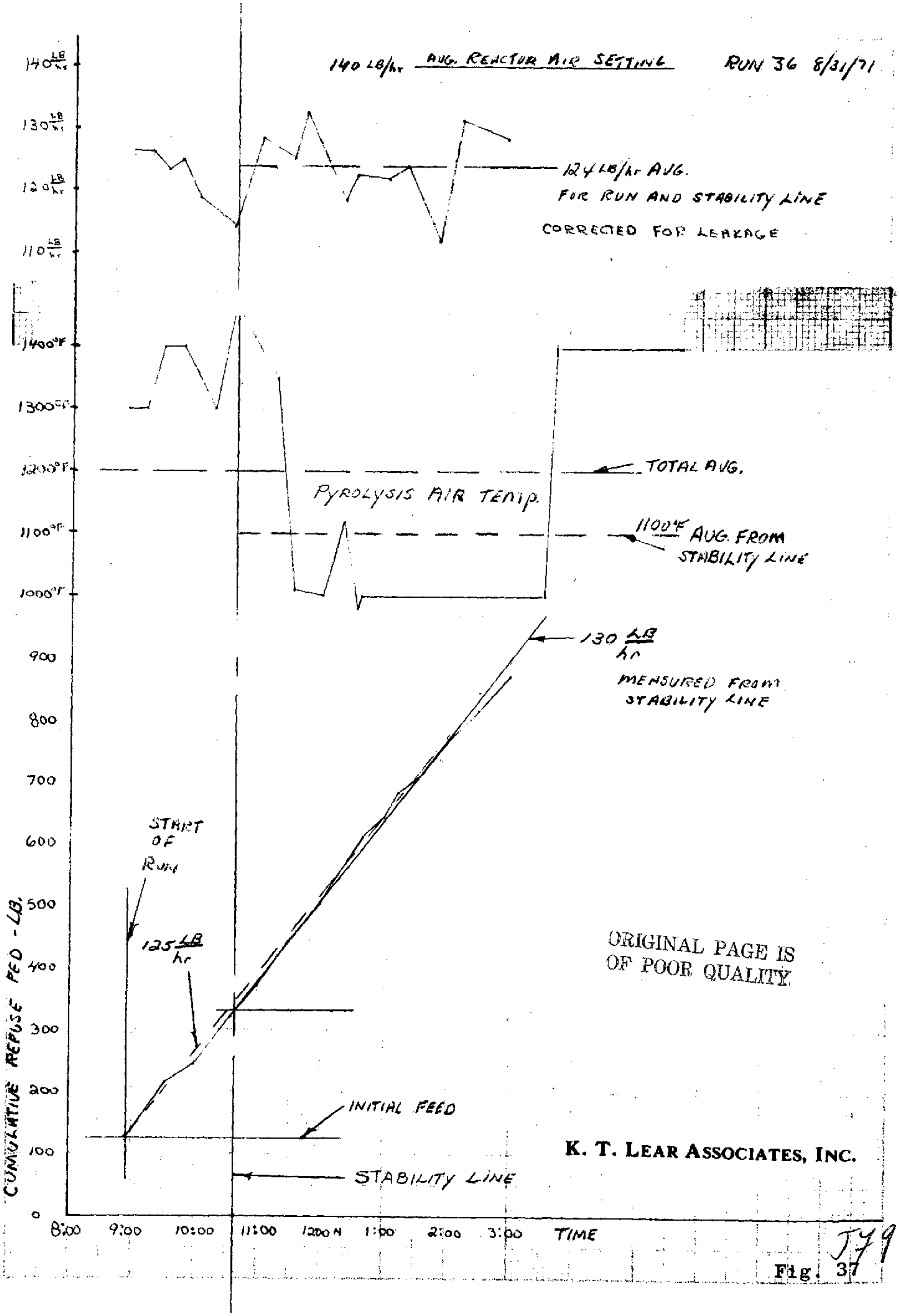

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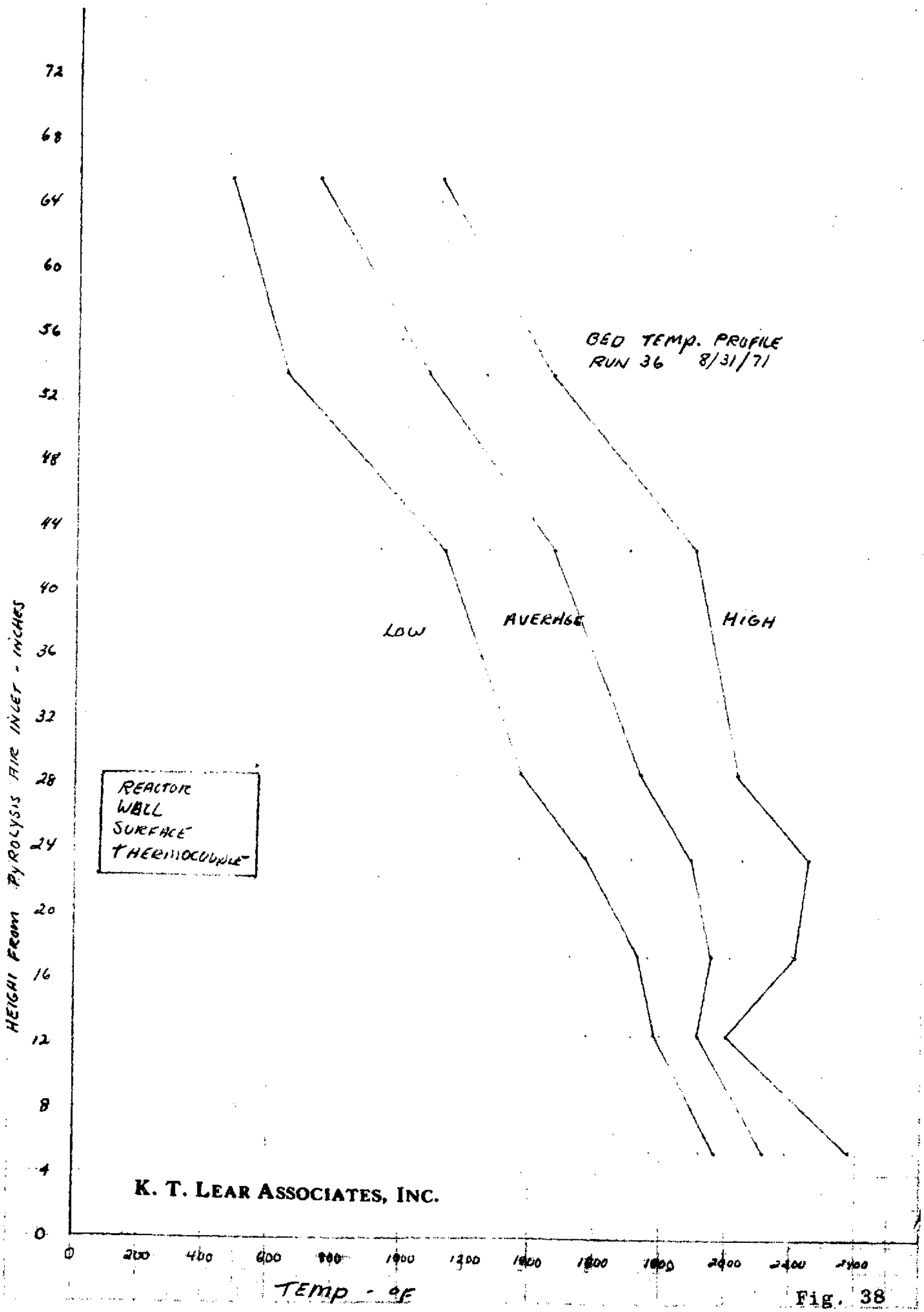
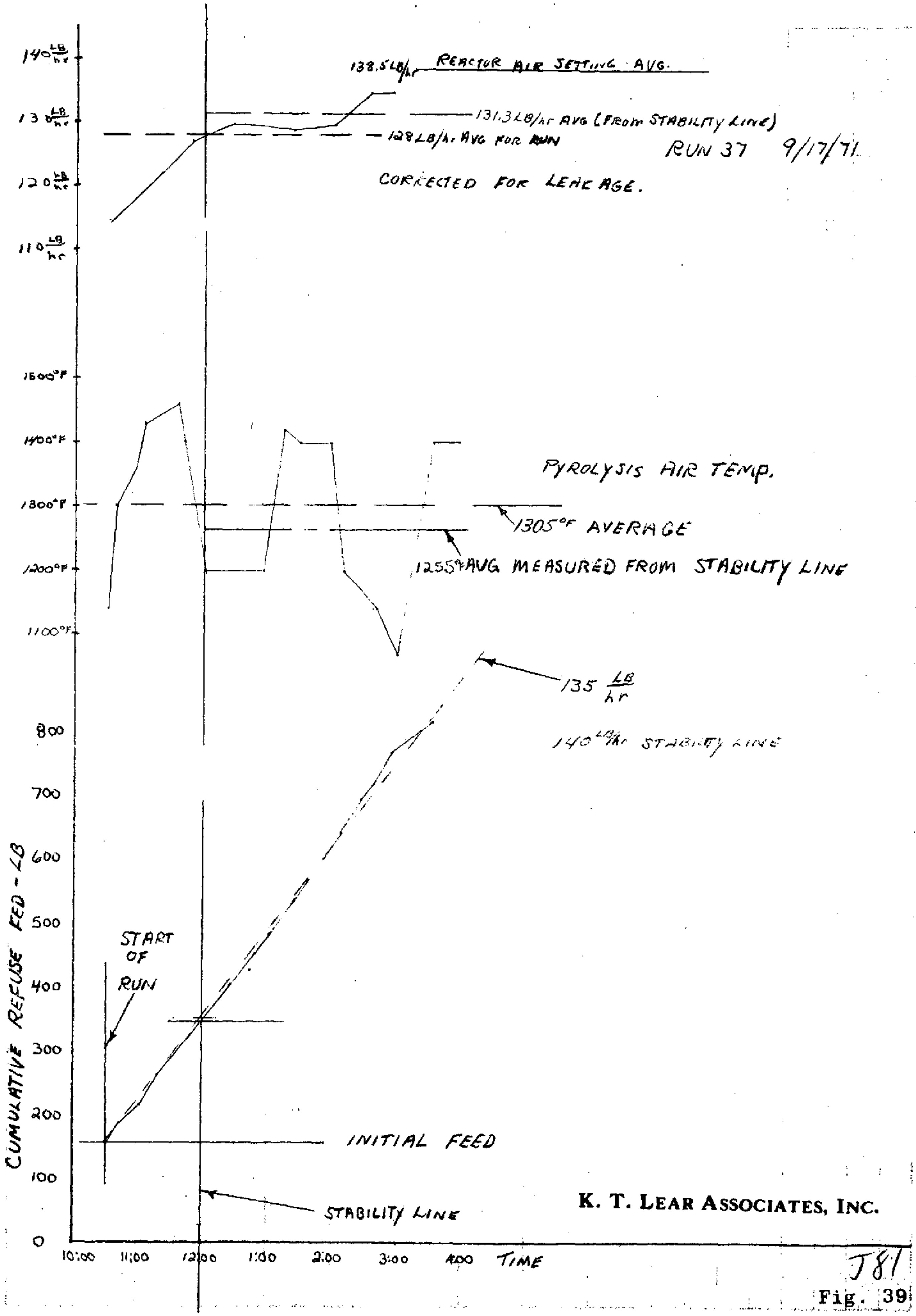
Fig. 37



K. T. LEAR ASSOCIATES, INC.

Fig. 38

J80



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J81

Fig. 39

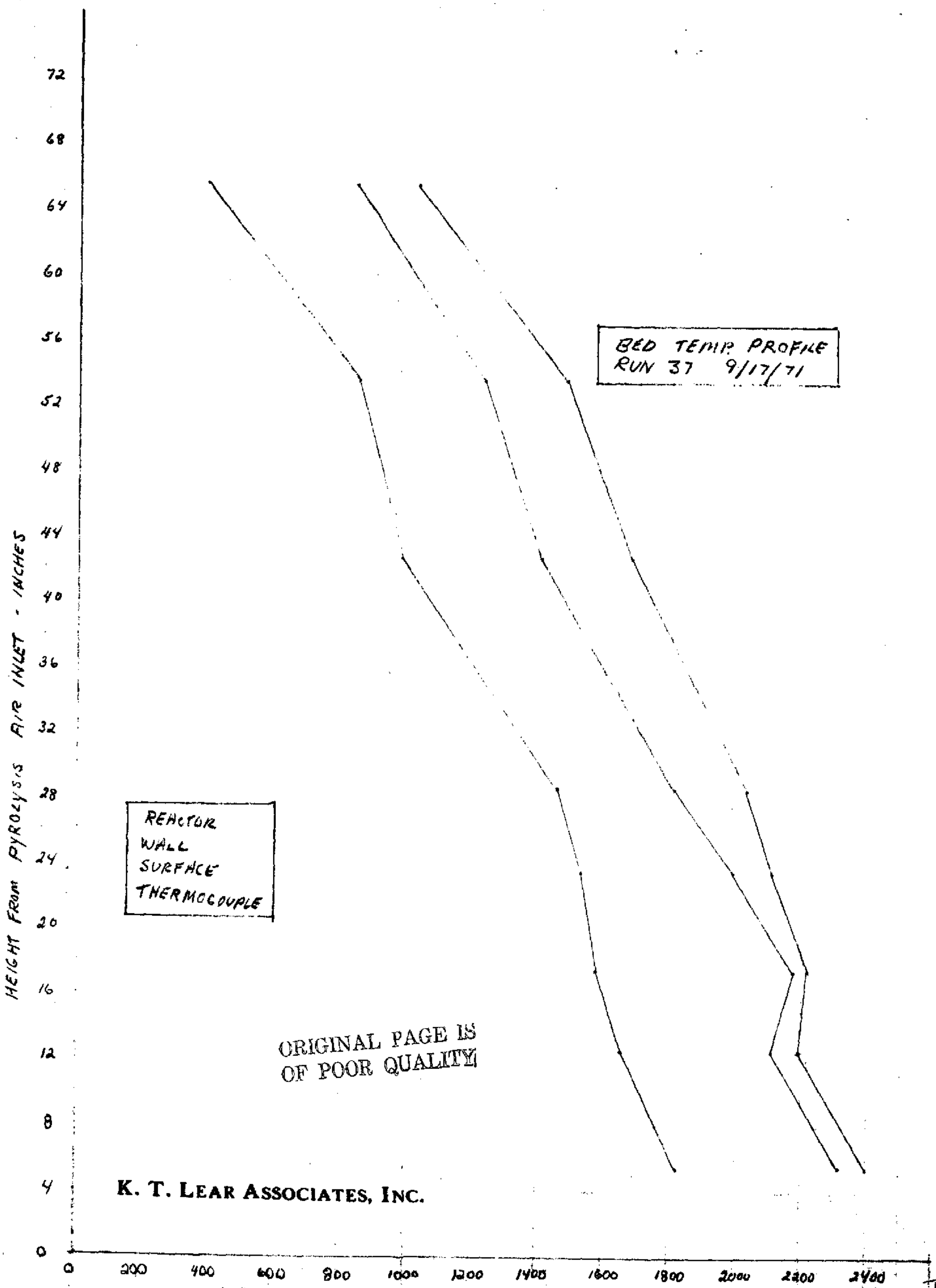
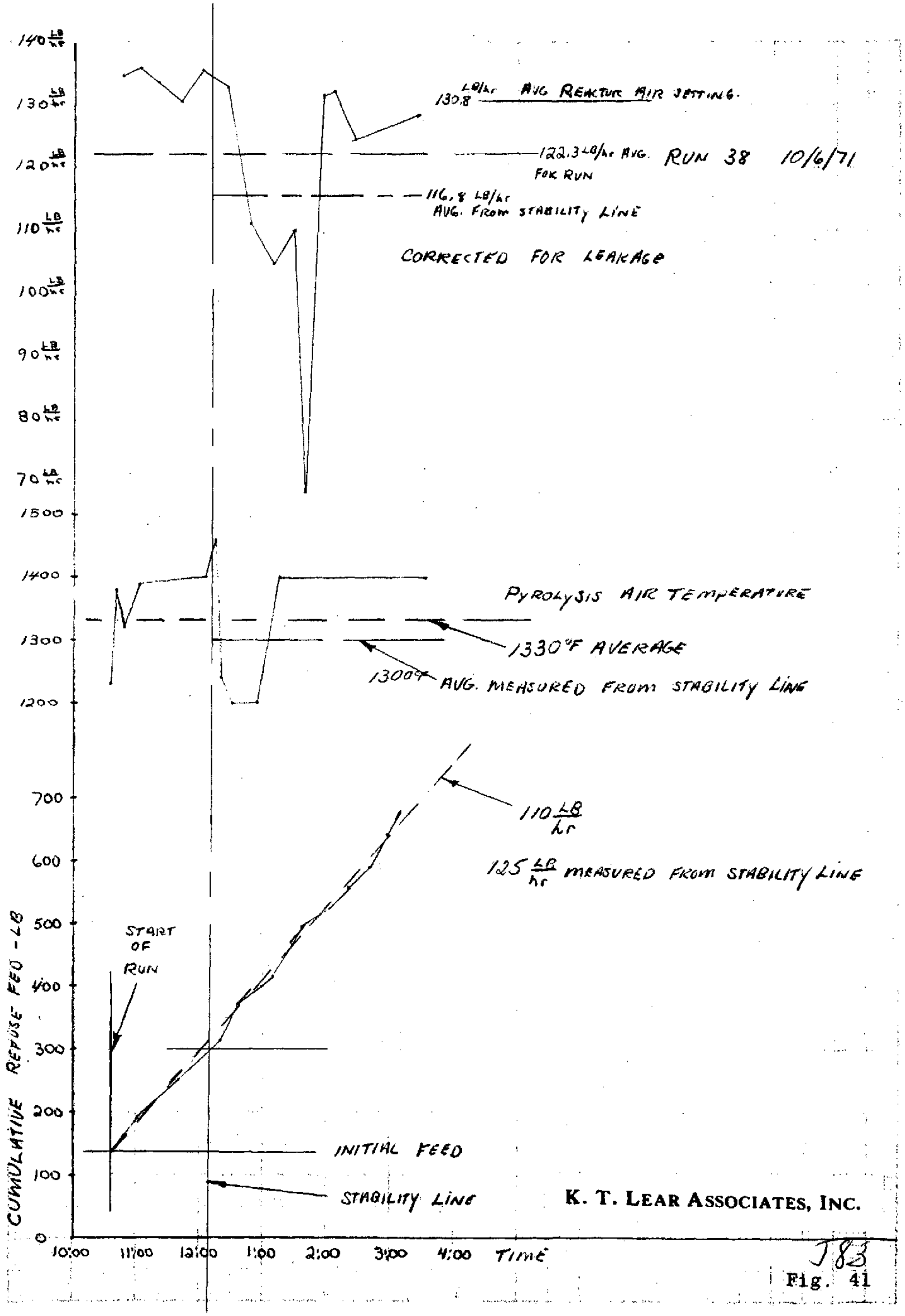

BED TEMP PROFILE
RUN 37 9/17/71
REACTOR
WALL
SURFACE
THERMOCOUPLE
HEIGHT FROM PYROLYSIS AIR INLET - INCHES
72
68
64
60
56
52
48
44
40
36
32
28
24
20
16
12
8
4
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
K. T. LEAR ASSOCIATES, INC.

Fig. 40

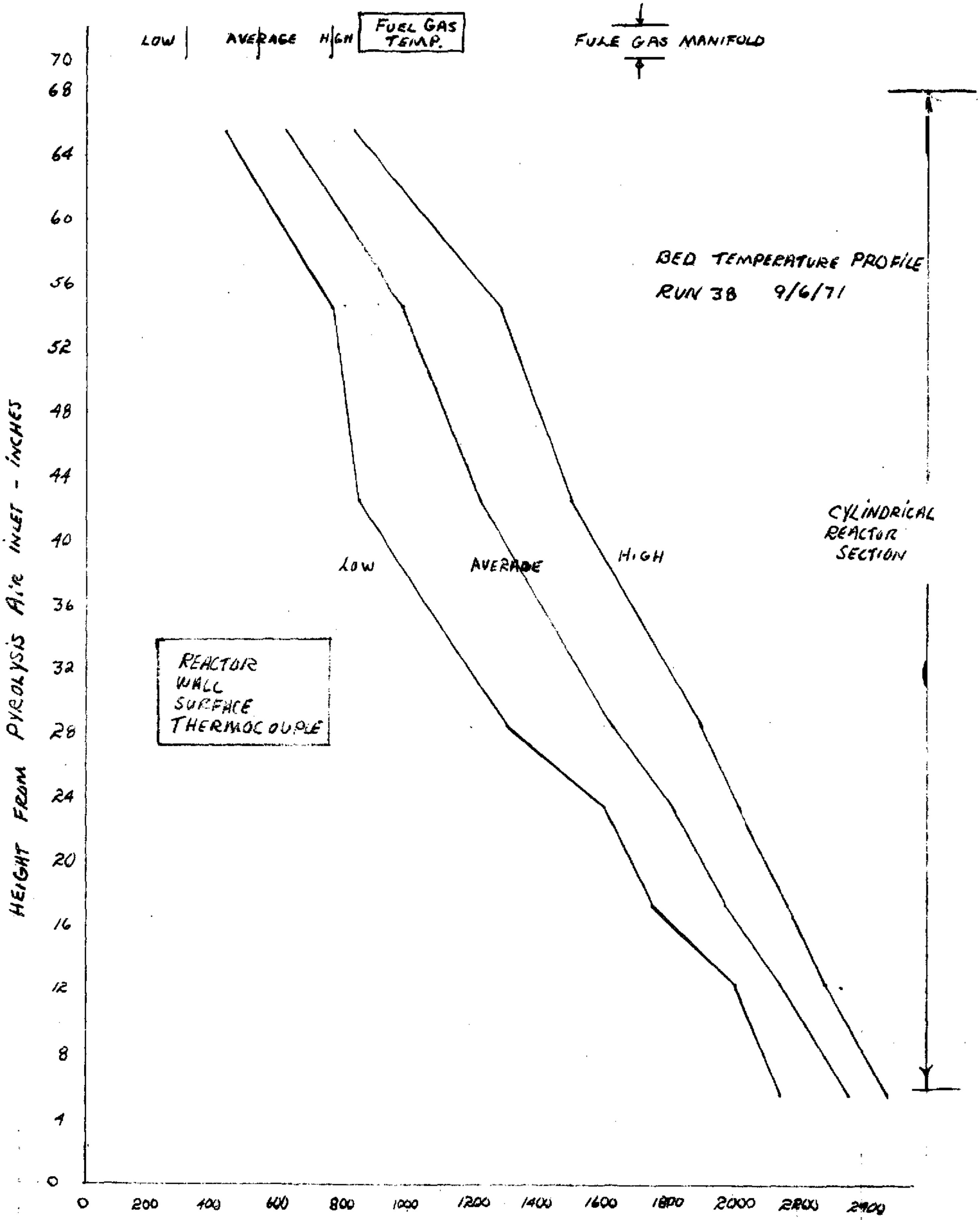
J82



K. T. LEAR ASSOCIATES, INC.

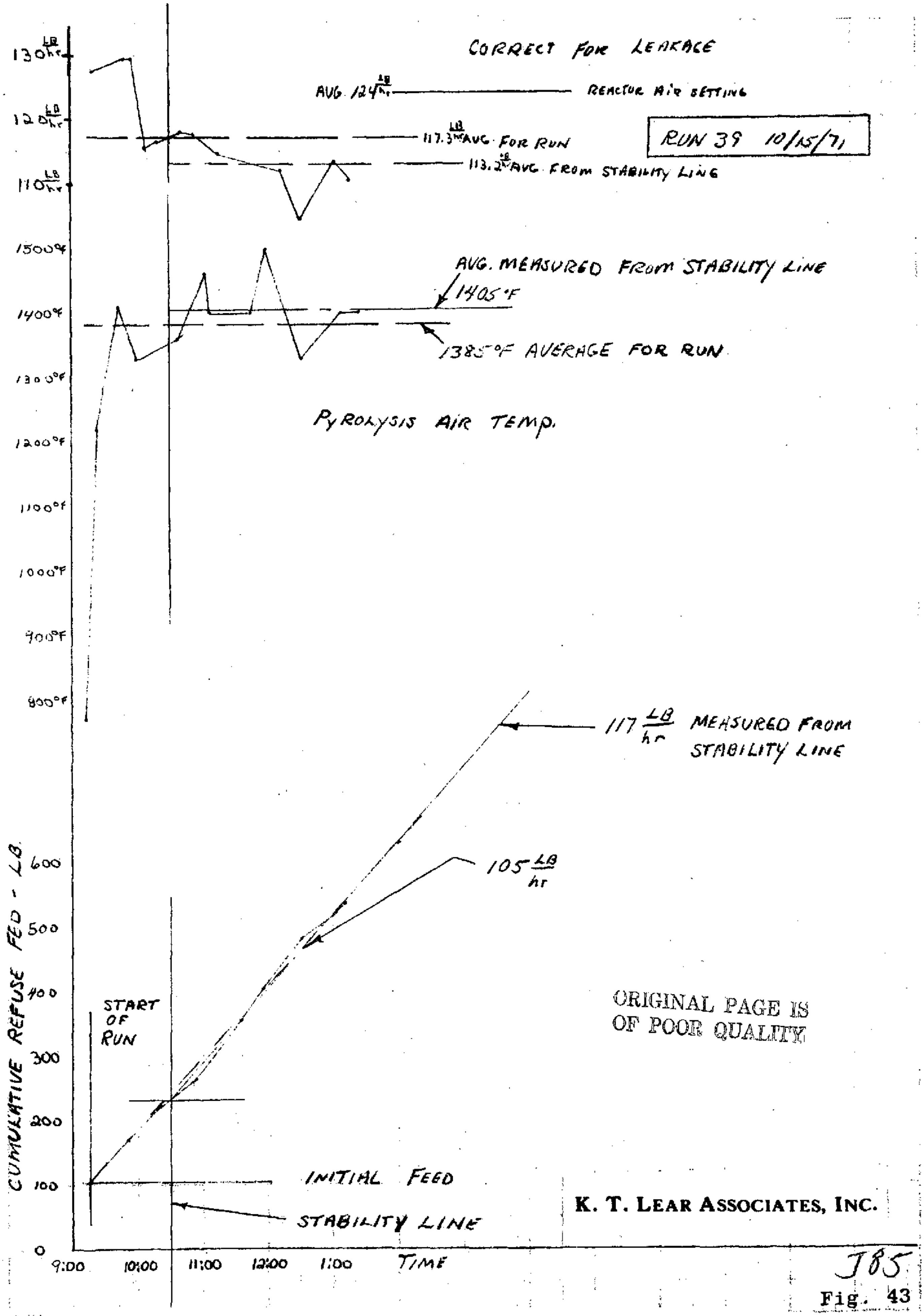
183

Fig. 41


LOW
AVERAGE
HIGH
FUEL GAS TEMP.
FULE GAS MANIFOLD
BED TEMPERATURE PROFILE
RUN 38 9/6/71
CYLINDRICAL REACTOR SECTION
LOW
AVERAGE
HIGH
REACTOR WALL SURFACE THERMOCOUPLE
HEIGHT FROM PYROLYSIS AIR INLET - INCHES
70
68
64
60
56
52
48
44
40
36
32
28
24
20
16
12
8
4
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400

384

Fig. 42



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J85

Fig. 43

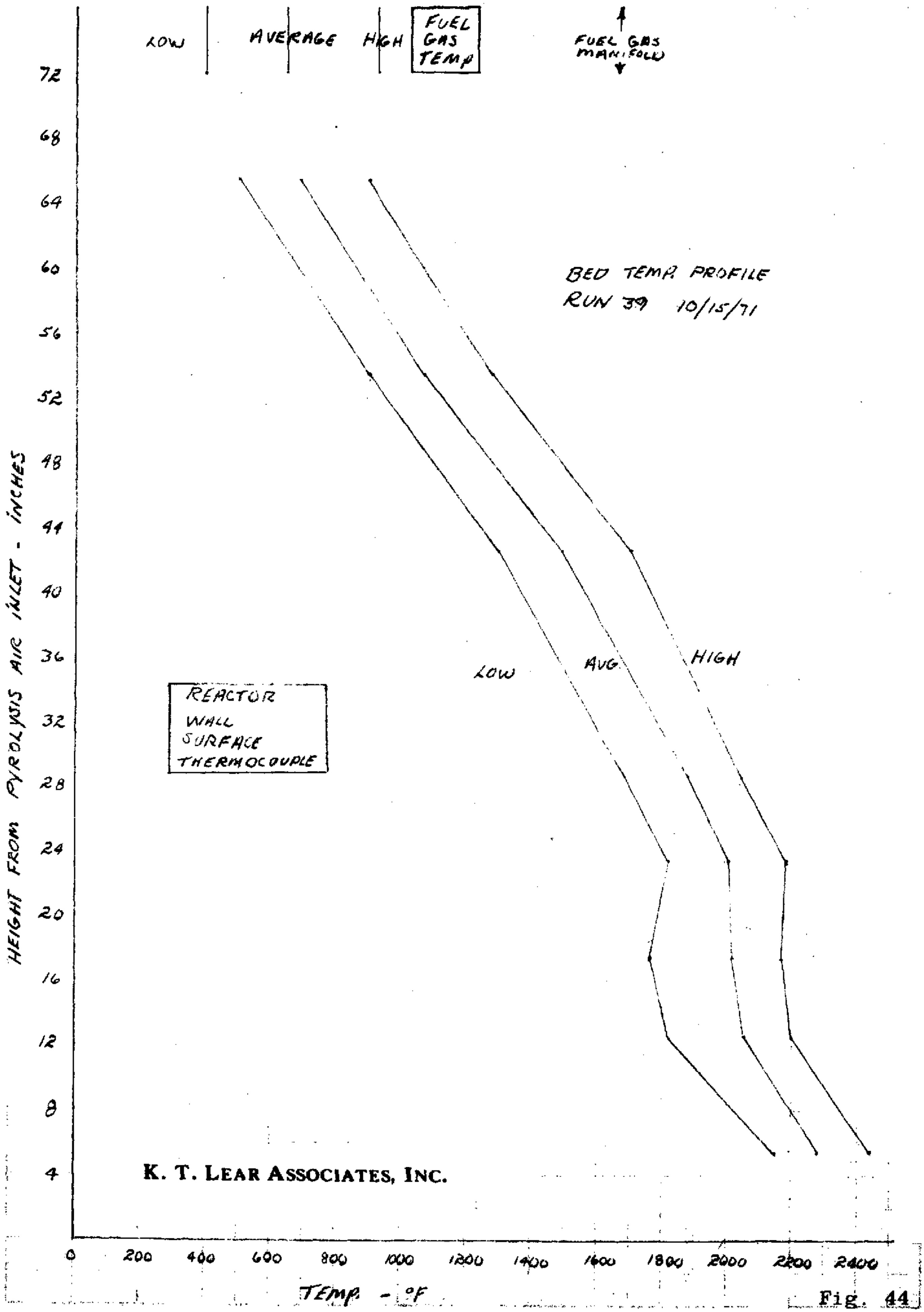

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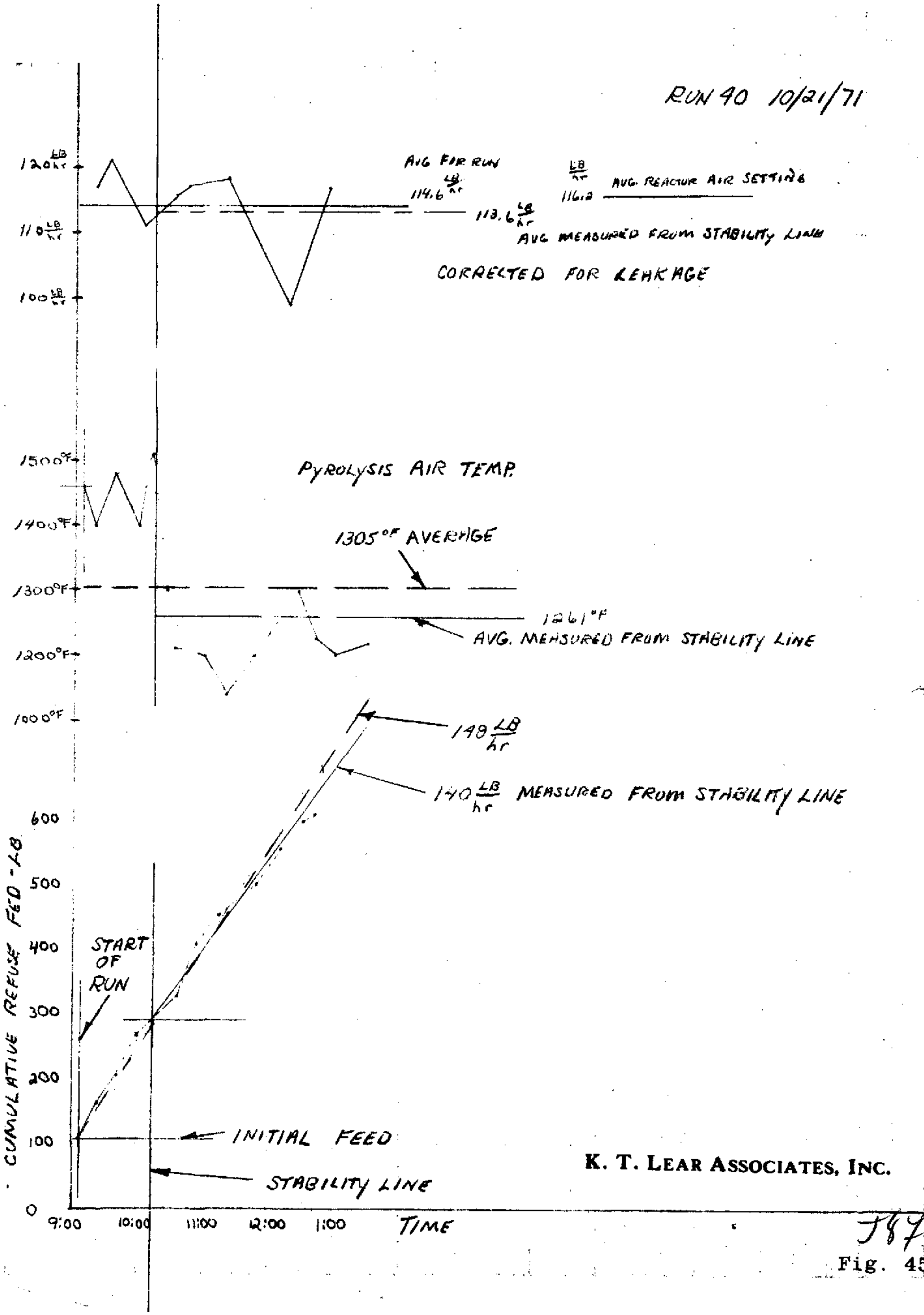
Fig. 44

786



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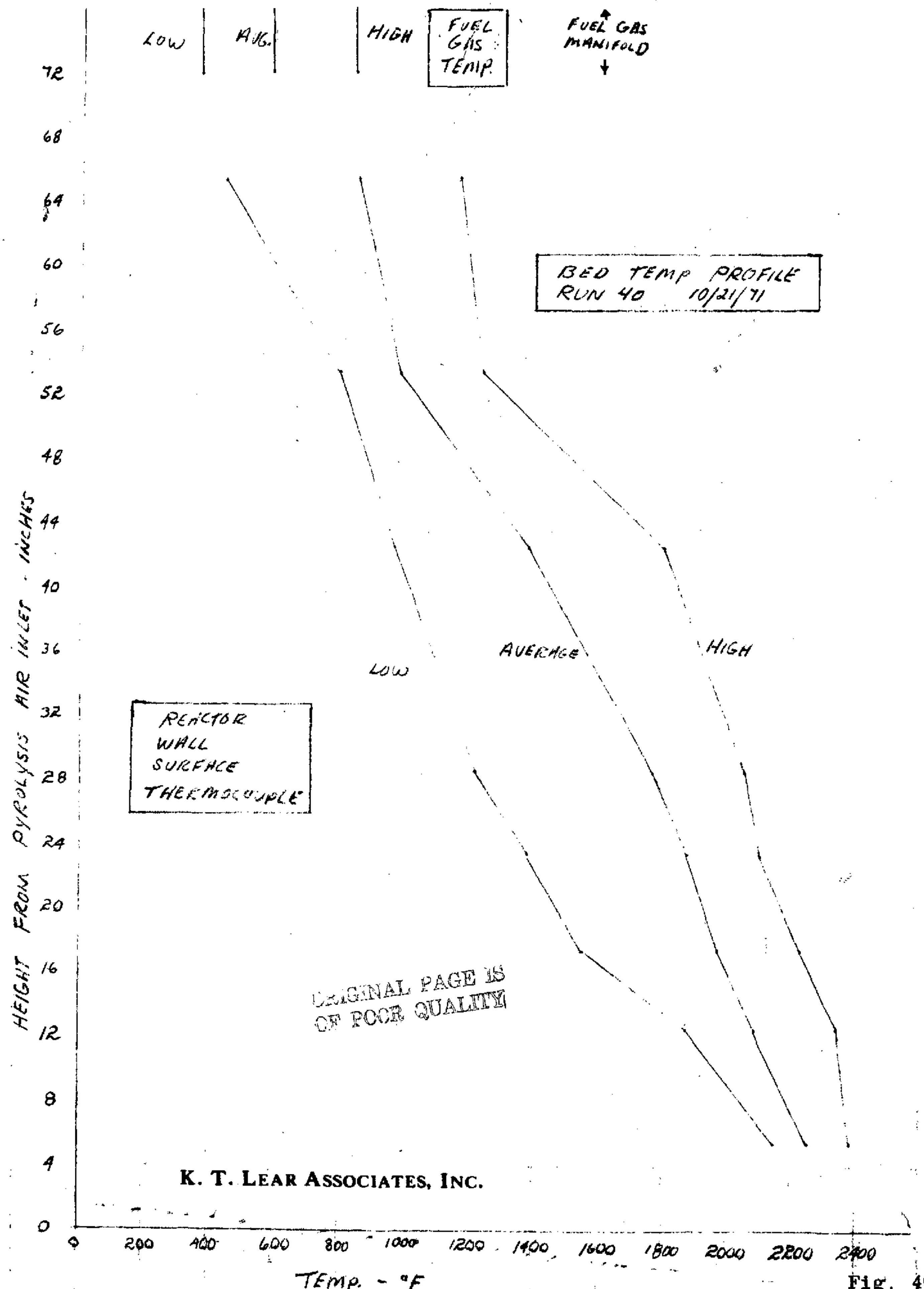

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Fig. 46